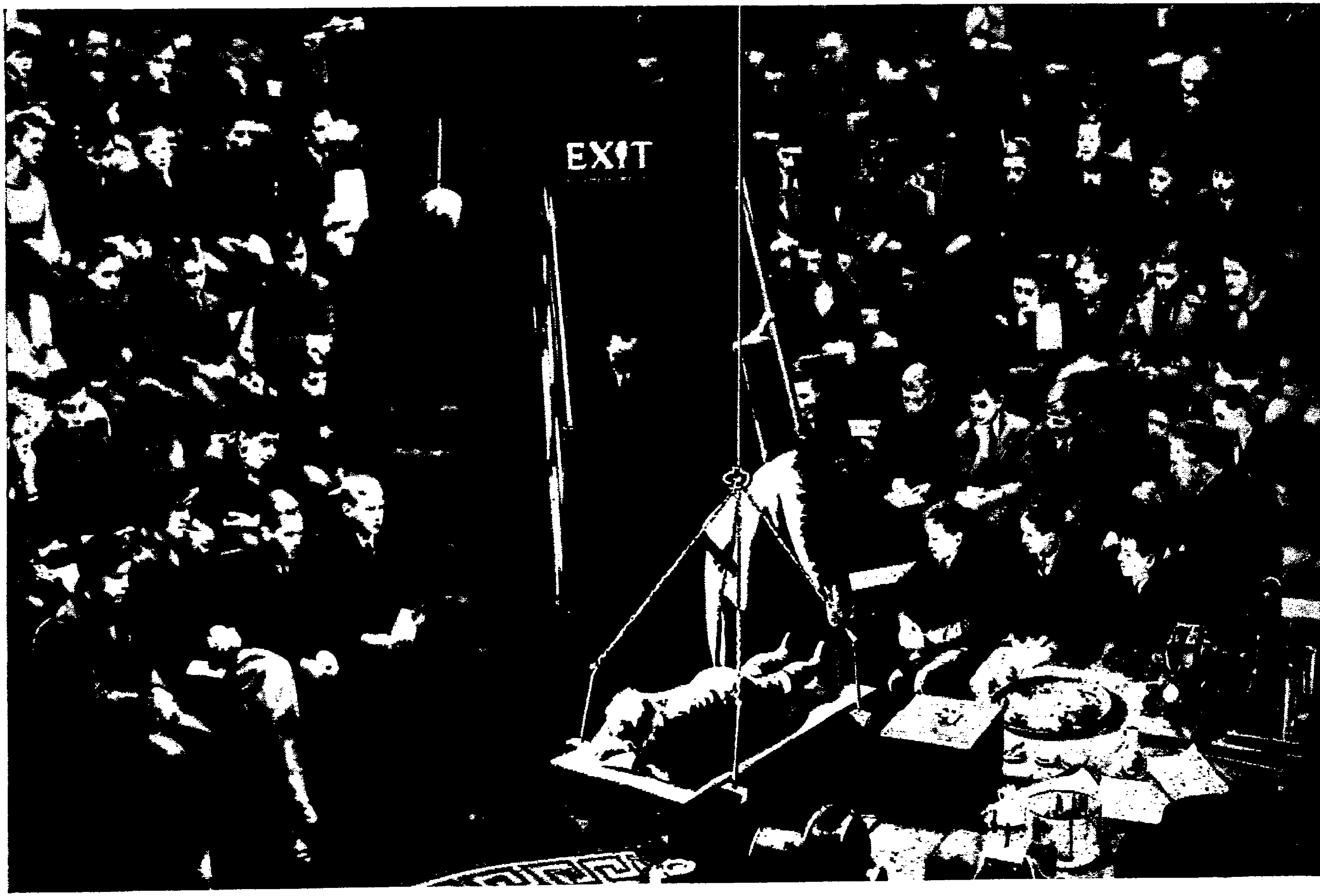
ELECTRICITY



A boy lying on a platform suspended from the ceiling is made to swing round by the attraction of an electrified ebonite rod held near his feet. (Fig. 3: *See* p. 6.) *'Daily Mail' Photograph*

[*Frontispiece*

ELECTRICITY

BY

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PREFACE

I was invited by the Royal Institution to give 'The one hundred and ninth course of six lectures adapted to a juvenile auditory' at Christmas, 1934, and have now put these lectures into the form of a book. The plan of the lectures has been closely followed in the six chapters of the book. The first three chapters deal with the behaviour of electrical charges, electrical currents, and magnets, and with such fundamental apparatus as cells, motors and dynamos. In the remaining chapters I have described in some detail the electrical apparatus which we see or use in everyday life. Chapter IV deals with power stations and the transmission of electrical current from one place to another, Chapter V with telegraphs and telephones, and Chapter VI with 'wireless.'

It is a common experience that there is a peculiar difficulty in grasping the ideas of electricity and magnetism. Nature has not prepared us to study electricity. The instincts and common sense which we acquire by handling objects make it comparatively easy for us to understand heat and light and sound, and the way in which machines work, but we seem to have no corresponding natural electrical sense although electrical devices of all kinds play so important a part in our lives. This electrical sense has to be acquired by studying that behaviour of things which is called 'Electricity,' and by trying to arrange our ideas clearly. When we succeed in acquiring it, we win the freedom of the electrical world. A transformer is thus seen to work in as natural and obvious a way as a typewriter,

and a wireless set is no more mysterious than a windmill. I have tried in this book to present the fundamental ideas of electricity in as simple a way as possible, and to make my account interesting by showing how these ideas are illustrated in familiar electrical appliances.

It has been much harder to write the book than to give the lectures. A lecturer at the Royal Institution has two great advantages. He is helped because experiments can be staged on so generous a scale by the immense resources of the place; he also has a most inspiring audience, composed of young people (of all ages) who come prepared to enjoy themselves, and being really curious are willing to meet the lecturer half way. I must hope my readers will be as indulgent and sympathetic as my audience at the Royal Institution. I have tried to judge how deeply I might go into various subjects by remembering the questions I was asked after the lectures. If parts of this book seem unduly difficult, it is because these questions gave me so high an opinion of the intelligence of the rising generation.

I wish to take this opportunity of again expressing my very warmest thanks to the Managers of the Royal Institution and to its Director, Sir William Bragg, for the honour which they did me in inviting me to give the Christmas lectures. I owe to my wife the suggestion that I should take 'Electricity' as my subject, and explain everyday electrical appliances. I have given on another page a list of the numerous friends who have helped me to prepare the lectures and to collect material for the book. Dr. E. C. Scott Dickson has read the manuscript and proofs, corrected many faults of grammar and awkward wording, and prepared the index, and I am deeply grateful for the help which he has given me.

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ACKNOWLEDGEMENTS

Many friends have helped me by preparing demonstrations for the lectures, supplying information and illustrations, and lending exhibits. I wish to express my warmest thanks to the following firms and individuals:

Mr. A. P. M. Fleming and members of the Research staff of Metropolitan-Vickers, Manchester, for spectacular demonstrations at the lectures and for supplying me with illustrations.

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Members of the staff of Kodak Ltd., and in particular Mr. Buckstone, for taking cinematograph pictures shown at the lectures and illustrated in this book.

I am indebted to the *Daily Mail* and to the *Sphere* for kind permission to reproduce photographs which were taken at the time of the lectures.

I wish to thank most warmly the members of the Royal Institution staff. Mr. Green and Mr. Bridges helped with the experiments in the lectures, Mr. Jenkinson made apparatus, and Mr. Mitcham met all my outrageous demands for an excessive number of electrical circuits on the lecture table. My own laboratory steward, Mr. Kay, was my chief assistant in the preparation of the course.

TECHNICAL TERMS

I have used technical terms freely in this book, explaining them where they first occur in its pages. They cannot be avoided in a subject like Electricity, which bristles with new conceptions. Scientists are often accused of making a subject difficult and mysterious by using technical terms. Sometimes this criticism is fair, for it is inexcusable to employ them where familiar words would serve. In many cases, however, no ordinary word has the correct or complete meaning we want, and it is much simpler to explain each technical word as the need for it arises and then to use it freely. Let us suppose an expert were asked to write an account of a football match, but forbidden to use such highly technical phrases as 'goal,' 'forward,' 'back,' 'try,' 'convert,' and so forth because he was writing for the general public and some of his readers might not understand them. His account would be intolerably long-winded. Anyone who wishes to take an intelligent interest in football should know enough about the game to understand what such words mean, and in the same way anyone who wishes to follow scientific descriptions should be prepared to learn what the most common technical words mean. Such words as occur in the book are printed in heavy type in the index, with a reference to the page on which they are explained.

No mathematical formulae have been given. On the other hand, I have tried to give the reader some idea of the magnitude of units in which electrical quantities are measured (ampere, volt, ohm, watt, henry, etc.) by quoting figures for familiar examples, because this is useful practical knowledge.

CHAPTER I

WHAT IS ELECTRICITY?

1. INTRODUCTION

We already use 'electricity' for very many purposes in our daily life, and we are coming to use it more and more. It is used to light our houses and streets and shops so brilliantly that people who live in cities are put to no inconvenience when daylight fails and the night sets in. Electric motors are used to give power for factories, to run trains and tramcars, and for humble tasks in the house like driving vacuum cleaners or sewing-machines or refrigerators. The current supplies warmth for electric radiators, electric cooking ranges, and electric irons. It rings the bells in our houses, works the signals on our railways, and sets off burglar alarms and fire alarms. Electricity is used to plate spoons and forks with silver, and to join pieces of metal together by welding. What is perhaps most important of all, electricity is used to convey messages from one place to another. We can send telegrams or cables to any part of the world, and our message arrives almost immediately at its destination. We can talk to each other over the telephone, and we can listen by wireless to programmes sent out from the broadcasting stations.

Although we use it for so many purposes already, it is clear that we have only begun to explore its possibilities. It is a new servant, able to do all sorts of

tasks which would have seemed magical to anyone who lived a hundred years ago.

In spite of the fact that we all use electrical devices so much in everyday life, I think most people would agree that there is something especially difficult about understanding how they work. Machinery which is made up of parts such as levers and wheels and cogs is much easier to understand. We can see how the different cogs gear into each other, or the levers press against each other, and our instinct and experience make us appreciate readily why the machine is built in that particular way. We only have to think of such things as water-wheels, windmills, pumps, cranes, typewriters, clocks, and steam engines, to realize the difference between ordinary machines and electrical machines. Mechanical devices are often quite complicated, but the forces and weights and reaction between their parts are something with which we have become familiar just by handling things ourselves.

It is very different in the case of electrical machinery. As an instance, suppose we take the ordinary meter in our house, which measures the amount of current used, and which is regularly read by the inspector before our quarterly bill is sent in. If we are allowed to look inside one of these meters, or better still have a chance to take one to pieces, we shall see an aluminium disc on a spindle (Fig. 1, Plate 1). When current is used, this disc rotates, and its turns are counted by the dials on the meter. What makes it rotate? There are two prong-shaped pieces of iron just above and below the disc, and the wire carrying current from the mains is wound round the prongs. There is also a permanent

magnet with poles on either side of the disc. I am sure most people would be perplexed if asked to explain just why this arrangement of magnets makes the disc turn round so as to measure how much current is being drawn from the mains.

A grid sub-station may be taken as another instance of the difficulty of understanding the significance of electrical machinery. We are becoming familiar with such erections. There is a fenced enclosure containing a lattice of girders (see Fig. 94, Plate 26). Wires on strings of porcelain insulators run beneath the girders, and are connected to a series of iron tanks with big insulating horns like antennae on their tops. What are all these things doing?

There can be no doubt that there is something mysterious and unfamiliar in all electrical gear. To understand it, we must study the behaviour of electricity, and know about the attractions and repulsions of electrical charges, the movement of electrical currents, the creation of magnetic fields by currents, and the creation of currents by magnetic fields. These names are in themselves alarming, because they describe new things which we do not meet with in ordinary life. Mankind has only very recently discovered how useful electricity can be, for Nature has kept the secret well. If there had been obvious examples in Nature of magnets and electrical currents, we would no doubt have studied them and used their principles to serve our ends long ago, just as we have used the forces of wind and water or the heat and light obtained by burning things. Nature sometimes provides us with an electrical display in the shape of a thunderstorm, but lightning is not something which

one can study calmly or put to useful ends. A fish called the torpedo, and the electric eel, have developed the trick of giving electrical shocks to their enemies or their prey. But here again it was very difficult to understand what was happening, or get any hint as to how we could use the same forces. Here is an old translation of Pliny to show how puzzled the ancients were by the torpedo, which is a kind of skate.

'The very crampe-fish tarped (torpedo) knoweth her owne force and power, and being herself not benummed, is able to astonish others.'

Man could not study the behaviour of electrical currents until he found some way of producing and controlling them. It is no wonder, therefore, that we have not developed an 'electrical common-sense' like the mechanical common-sense which has become almost instinctive. There is really nothing more mysterious about electrical forces than about the forces which lift weights or pull trains, in fact it is the latter which are the more complicated. We must, however, make ourselves thoroughly familiar with a few important rules about electrical behaviour, which at first sight seem strangely unlike anything to which we are accustomed.

In the first three chapters we will study these rules, testing them in many ways till they seem natural and obvious. I then wish to describe the working of various electrical machines and devices, and I think you will see how easy it is to understand them once you have become 'electrically-minded.'

I am writing this book for those who are curious about electricity and want to undertake the adventure

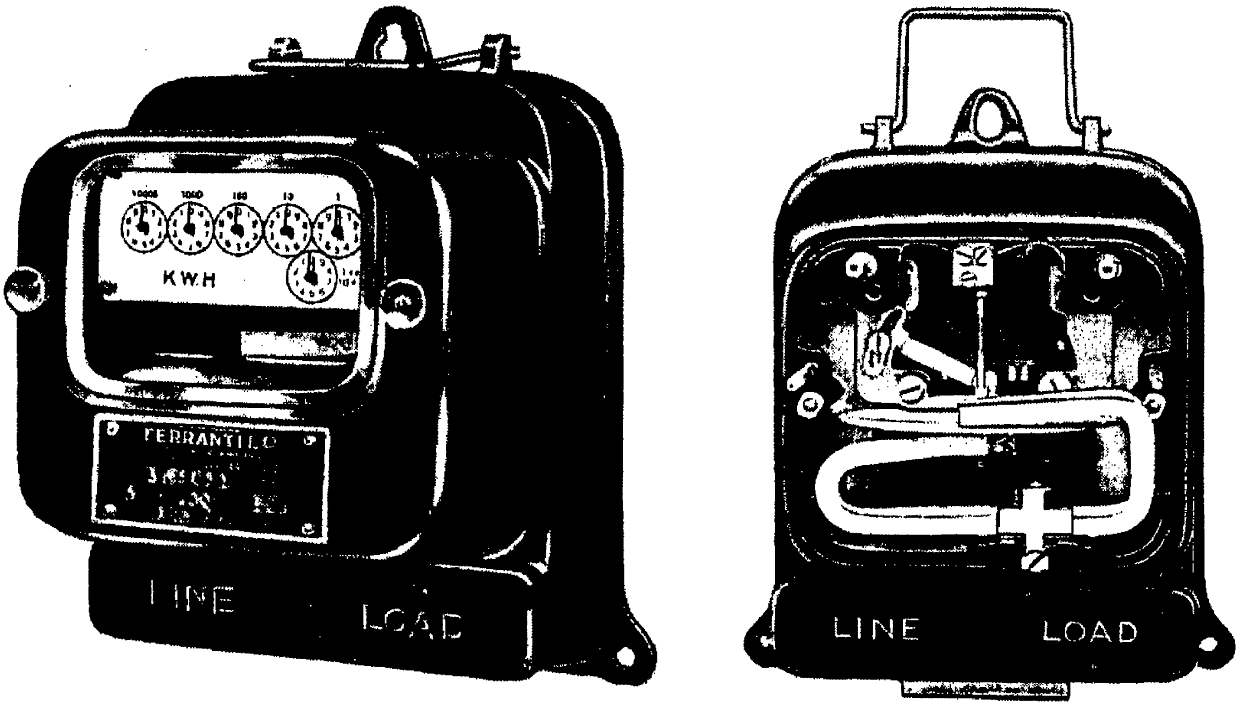
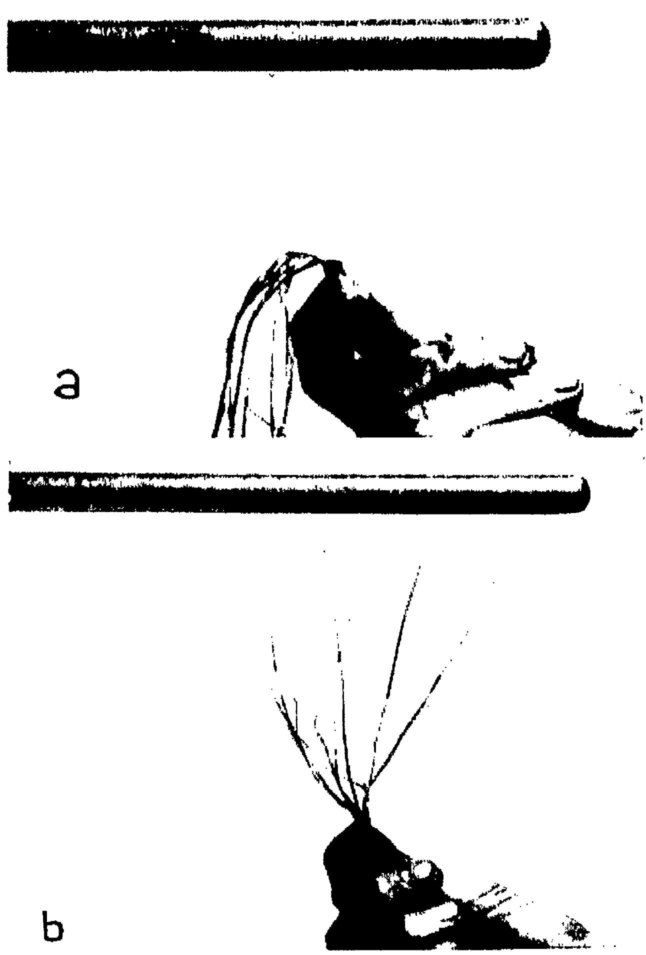


Fig. 1. An alternating-current meter (*Ferranti*)



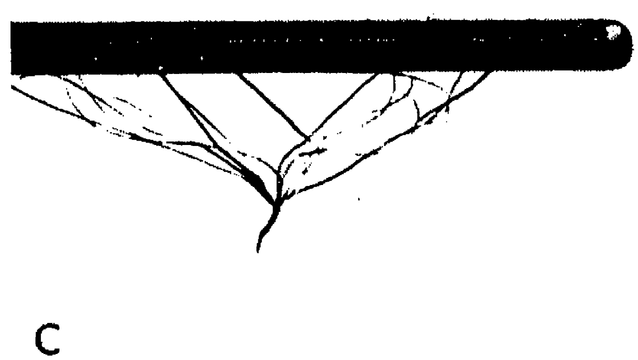


Fig. 2. An ebonite rod and a tuft of paper strips.

(*a*) Before electrification.

(*b*) The rod is electrified by rubbing. Note the mutual repulsion of the strips due to their induced charges.

(*c*) The tuft is released and flies to the rod.

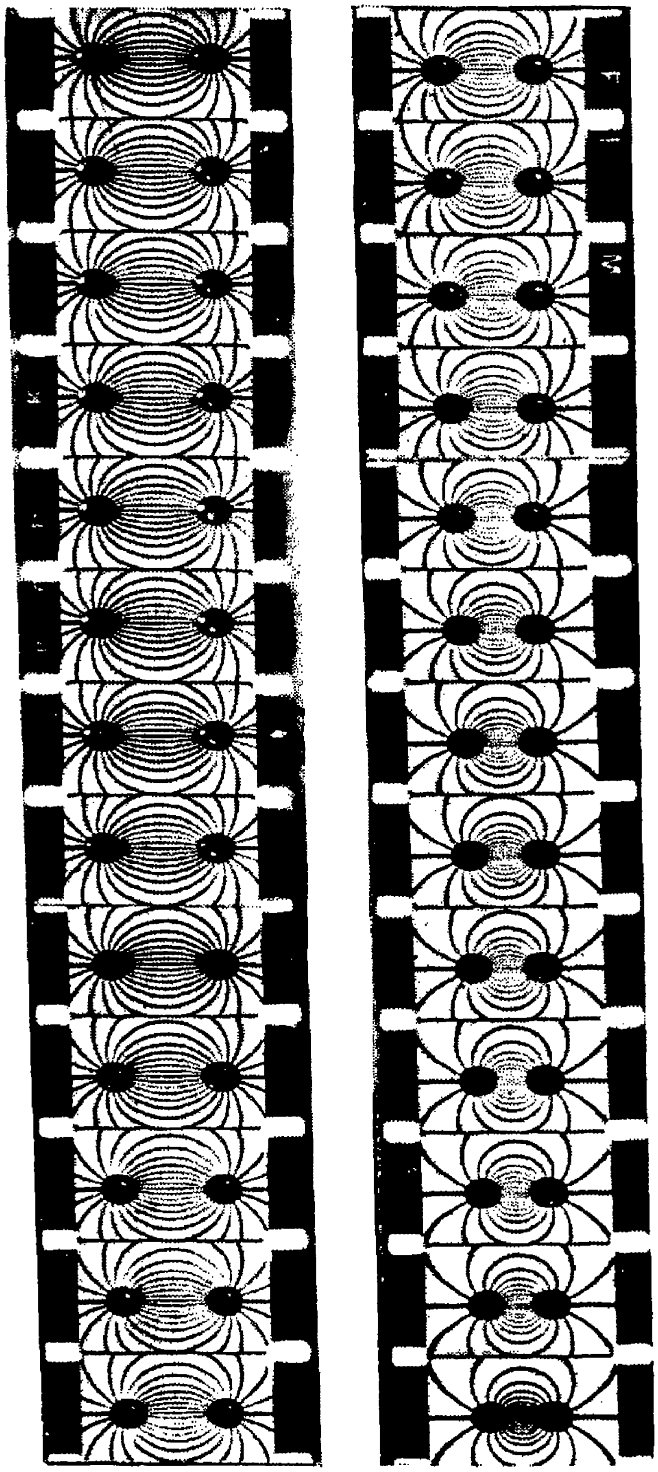


Fig. 10. A 16 mm. cine film showing the movements of the lines of force when two balls with equal charges of opposite sign move together (*Kodak*)

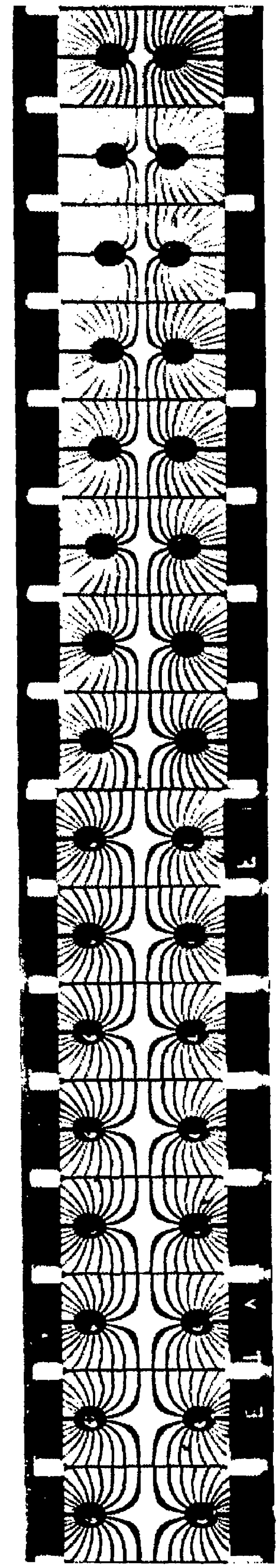


Fig. 11. (Right). A similar film for the case of balls with equal charges of the same sign (*Kodak*)

of acquiring an electrical common-sense. It requires a certain amount of hard thinking to get things clear in one's head. Just because the ideas are strange, and new words must be used to explain them, books on electricity have a tendency to seem very dry and dull. It is much harder to make the subject interesting in a book than in a lecture, when experiments can be done which are fascinating because such curious effects can be produced. I must manage as best I can with diagrams and pictures, and hope my readers will have a chance to see the actual experiments, or, best of all, will try them for themselves.

2. ELECTRICAL CHARGES

I can remember how puzzled I used to be as a boy when I first became interested in science, because the word 'electricity' seemed to be used for such different things. When anyone's hair gave out a crackling sound on dry days when brushed, it was said to be 'full of electricity.' At the same time there were power stations run by 'Electricity Boards' and our houses were beginning to be 'lit by electricity.' What was the connection between these uses of the word?

The connection will become clear as we go on. Let us in the first place study the 'electricity' we get by rubbing things, or to put it more precisely, the behaviour of electrical charges.

When a piece of amber is rubbed, it can attract light objects. This has been known for a very long time. It is said to have been discovered by Thales (600 B.C.), but it is quite likely to be a much older discovery. Prehistoric man probably wore pieces of amber as

primitive jewellery, and can hardly have failed to observe that if it was rubbed when it had become warm and dry in the sun, it picked up straws and dried leaves. One can imagine him ascribing all sorts of magical properties to this marvellous yellow stone. No other natural substance (amber is a kind of hardened gum) has this curious property to the same extent, and so it came about that the Greek word for amber (electron) has given its name to electricity.

We can show the effect in a striking way if we rub an ebonite rod with a piece of flannel and place it near something very light. Thin strips of tissue paper leap towards the rod and stick tightly to it (Fig. 2, Plate 1). It is even better to use the white ashes of burnt paper, or small pieces of thin aluminium foil. Owing to their extreme lightness they will leap up to the rod when it is held a foot above them. Electrification can be obtained by rubbing a fountain-pen or a pipe-stem on one's sleeve. A cotton thread hanging near will fly towards it.

It is possible to show the force of attraction on quite a heavy object. Fig. 3 (*Frontispiece*) shows a boy lying on a platform which is hung by a wire from the ceiling of the lecture theatre at the Royal Institution. By holding an electrified ebonite rod near his feet, the platform can be made to turn in one direction or the other. It moves slowly at first, but with a little patience one can coax it to swing right round.

When a rod which has been rubbed acquires this property of attracting other bodies, we say that it has got an electrical charge or is electrified. In reality, everything gets electrified by rubbing, but in the case of

most substances the electrical charge immediately leaks away like water through a sieve. Such substances are said to conduct electricity. Other materials like amber, glass, ebonite, wax, and sulphur are non-conductors of electricity or insulators. When a charge is produced on their surfaces, it leaks away extremely slowly and remains where it has been created for a sufficiently long time to enable experiments to be made with it. A brass rod can be electrified by rubbing it with a piece of flannel, if the rod is fixed to a glass or ebonite handle. When the brass rod itself is held, any electrical charge leaks away because the metal and one's fingers are conductors, but when the non-conducting handle is held the charge remains on the rod.

In making any experiment on electrical charges, it is necessary to have the insulators quite dry, for moisture on the surface conducts the charge away. The insulators can be dried by warming them before the experiment. Many substances which we are not accustomed to classify as good insulators become so when they are very dry. In a cold winter climate such as exists in Canada and the northern part of the United States, the air contains very little moisture because of the low temperature, and when it is admitted to the houses, which have very efficient central heating, it becomes extremely dry. Under such conditions a carpet is an excellent insulator. When one walks over the carpet, the friction between shoes and carpet produces quite a large electrical charge, which accumulates on the body since it cannot escape through the carpet. In this case one's body is the conducting rod and the carpet is a cloth which is rubbing it. On reaching out

one's hand towards a metal door-knob, a crackling spark passes and a prick is felt. When I was in America one winter, a small girl of my acquaintance used to amuse herself by skipping across the carpet and then presenting her finger tips to the sensitive nose of the dog asleep before the fire. I have been told by Canadian friends that it is possible to light a gas jet in

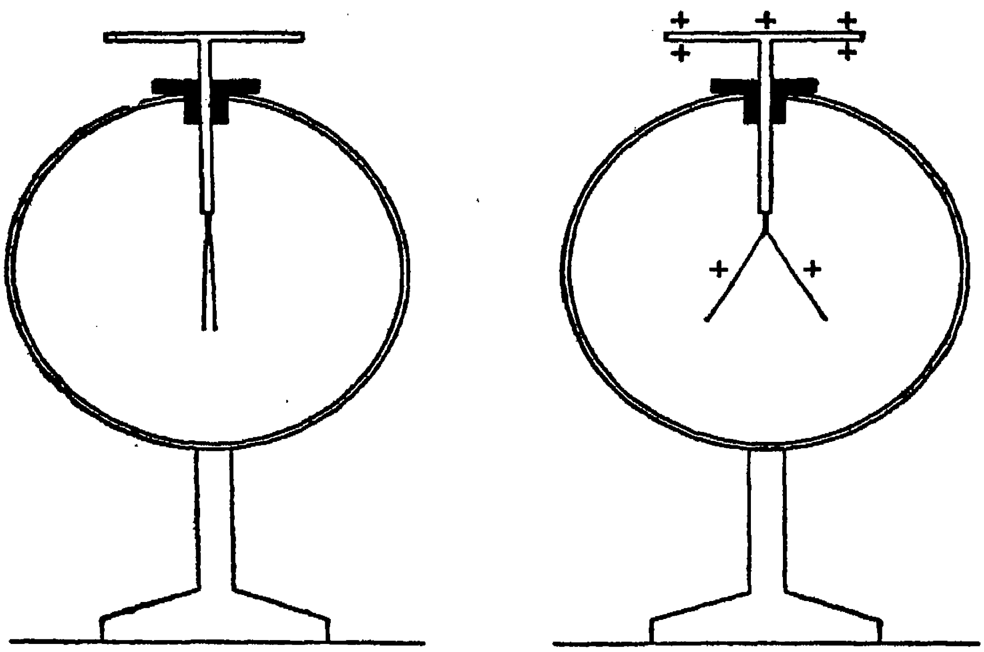


Fig. 4. The gold-leaf electroscope.

winter with one's knuckles after walking across the carpet. In this country the air is too damp for such an experiment, especially in a lecture room, but it is easy to show the charging of one's body by walking on an insulator.

On the occasion of the Christmas lectures, we placed a sheet of ebonite on the floor, and I stood on it. By shuffling my feet, I could give myself an electrical charge which was too weak to give a spark but could be shown by means of a gold-leaf electroscope (Fig. 4). In this instrument two pieces of gold leaf are stuck to a wire and hang down side by side. The wire is in a

case with glass sides, and comes up through an insulating stopper to a little plate on top. If this plate is touched by a charged body, and so given a charge, the gold leaves spread out because they have a similar charge and repel each other (see next paragraph). Gold leaf is used because gold can be beaten out till it is extremely thin and light. An image of the leaves was projected on a screen by a lantern, so that the audience could see them move.

In this experiment we showed an effect which I wish to explain later, though it is convenient to refer to it now. If one just shuffles one's feet on the ebonite, the leaves of the electroscope hardly diverge at all. If then one rises on tip-toe, or better still stands on one toe in the attitude of the statue of Eros in Piccadilly Circus, the leaves spread more widely, showing that a larger share of the charge has passed into the electroscope. On sinking back into the original position, the leaves collapse again.

I have heard people say that they are 'full of electricity,' because they frequently find that their hair becomes electrified when brushed. It gives out a crackling noise, and the separate hairs stand away from each other. They are quite right as to being full of electricity, because as we shall see our bodies like all other forms of matter are built of electrified particles. In this sense everything is made of electricity. The real reason why their hair is so often electrified, however, is that it is exceptionally dry; though this is not always a tactful explanation to give to one's friends.

3. POSITIVE AND NEGATIVE ELECTRICITY

Electrical charges are of two opposite kinds, positive and negative. Positive and negative charges attract each other, but positive repels positive and negative repels negative. When electrification is produced by rubbing, the opposite charges are generated in equal amounts. An ebonite rod rubbed with a piece of flannel becomes negatively charged, and the

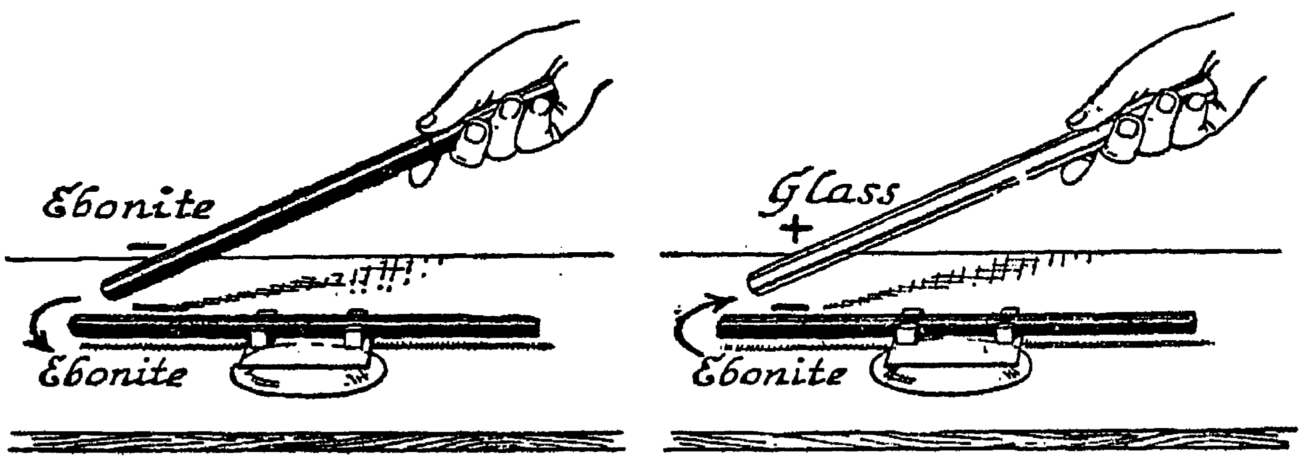


Fig. 5. Electrostatic repulsion and attraction.

flannel becomes positively charged. When a glass rod is rubbed with silk, it is the rod which acquires the positive charge and the silk which is negative. Charging by friction is a complicated effect, and as far as I am aware, it is impossible to predict which body will get the positive charge; we can only quote the observed result for each pair of substances.

In Fig. 5 an ebonite rod is laid on a carriage made by sticking two notched corks to a piece of glass. The carriage rests on something which is smooth and slightly rounded, such as a watch-glass, the object being to allow the ebonite rod to swing round easily. If the ebonite rod is rubbed and balanced on the carriage, and another ebonite rod which has been

rubbed is brought near one end, the first rod will swing vigorously away from the second. On the other hand, if a glass rod rubbed with silk is brought near, it will attract an end of the electrified ebonite rod. The arrows show which way the rod moves.

There are endless experiments which illustrate the attraction and repulsion, some of which are very pretty. In the Christmas lecture we showed an experiment[1] in which two people stand on platforms about six feet apart which are insulated from the floor by glass legs. The platforms are connected to an electrical machine which charges the one positively and the other negatively. Each person blows soap bubbles with a pipe and bowl of soapy water. When the electrical machine is not working, quite big soap bubbles can be blown. If the machine is started up so that the bubble-blowers are charged, the soap bubble strains away as it is blown, as if something were trying to tear it from the pipe. It breaks off while still quite small, and dashes away through the air from the one person to the other. The soap bubble on the positive side is positively charged; it is repelled by the man who blows it, and attracted by his vis-à-vis. The same thing happens to the negatively charged bubbles blown by the other man, so that the air is filled with soap bubbles crossing the intervening space. In doing the experiment one's face gets quite wet because the electrified spray made by the bubble-blowing also rushes through the air from one person to the other. Sometimes two bubbles of opposite sign meet half-way. They are then 'discharged,' because their opposite electrifications

[1] I am indebted to Professor Tyndall of Bristol University for suggesting this experiment to me.

neutralize each other, and the bubbles fall towards the ground.

Why does a charged rod attract light objects in its neighbourhood? This is not quite obvious at first sight. We have seen that positive attracts negative, but when we bring the rubbed ebonite rod near scraps of paper or bits of aluminium foil, these latter objects are not originally charged with electricity of either sign.

I wish at a later stage to explain many electrical

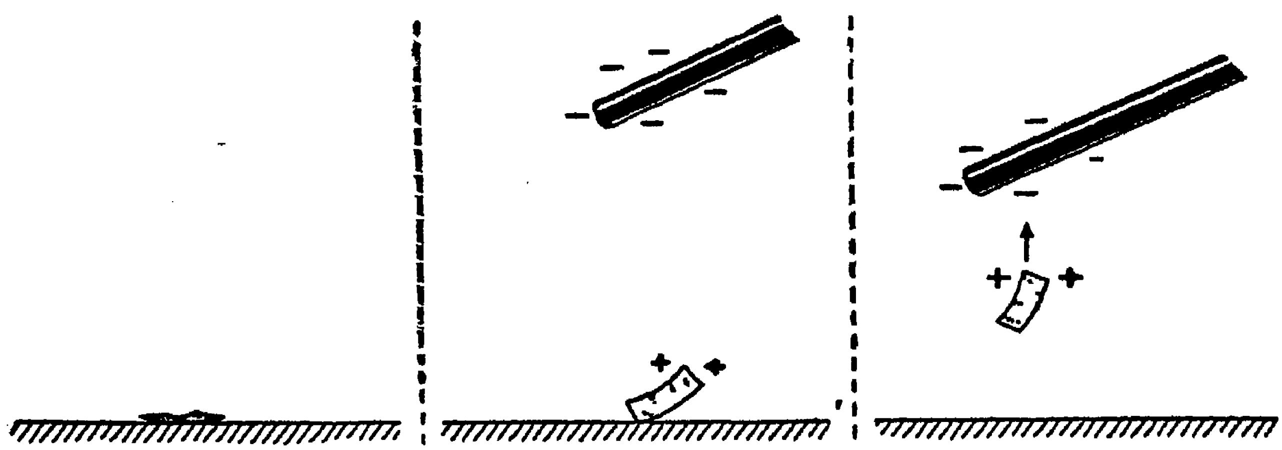


Fig. 6. A charged rod attracting a piece of foil.

phenomena by a picture of 'lines of force' which shows what is happening in a much more powerful and graphic way. For the present a picture like that in Fig. 6 will suffice. We will suppose that a scrap of aluminium foil is lying on a conducting surface such as a metal tray, and that the ebonite rod is brought near it from above. The foil is a conductor, so that electrical charges can move about in it. As the rod approaches, the uppermost part of the aluminium foil becomes positively charged, as if the ebonite rod were dragging positive electrification into the part nearest it and driving negative electrification away from that part by repulsion. We can see the foil bending up

towards the rod, and finally standing on tip-toe, as it were, straining towards it. Finally the attraction between the charges overcomes the weight of the foil and it dashes up towards the rod.

The electrification of the body when the rod comes near it is seen very well in the photographs in Fig. 2*b* (Plate 1). The experimenter is holding a small tuft of tissue paper streamers in his hand, beneath the

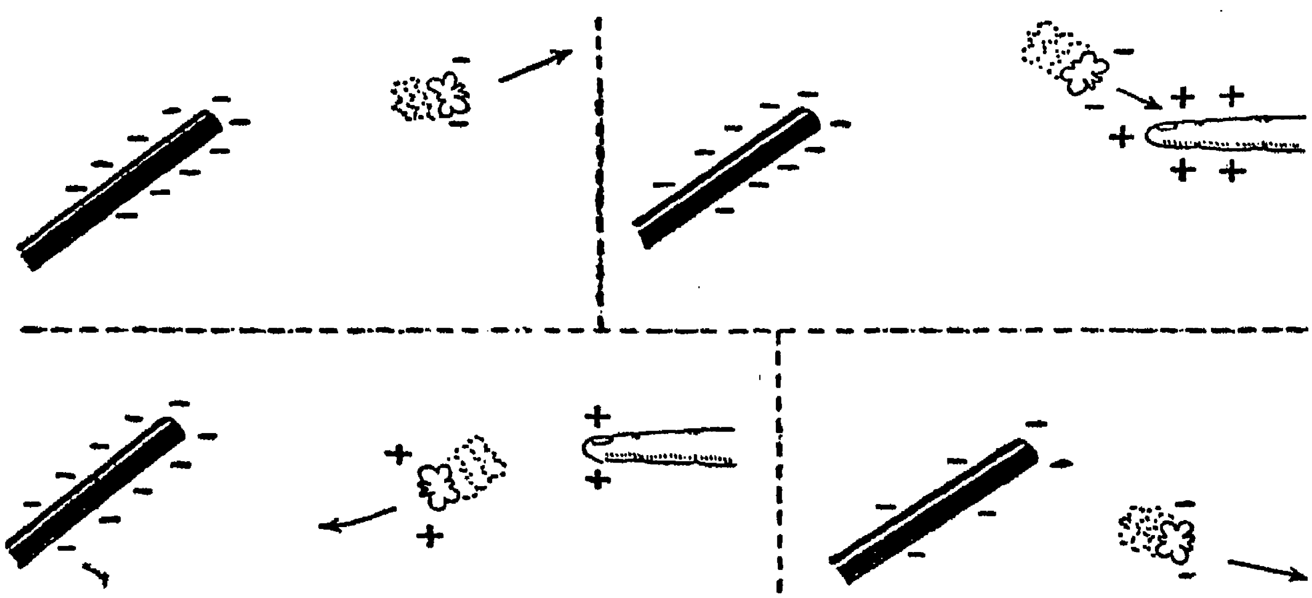


Fig. 7. The electrical butterfly.

electrified ebonite rod. Not only do the streamers strain towards the rod, but also *they repel each other strongly* as you will see by the way they spread apart in the photograph. The repulsion is due to their positive charge, *induced* by the negative charge on the rod. When the tuft is released it flies to the rod as in Fig. 2*c* (Plate 1).

A piece of foil at first sticks to the rod, but often after a second or two it will be seen to dash away again just as violently. Though the ebonite rod is a good insulator, charges do actually leak about slowly in it. When the foil touches, the negative charge on that part of the

rod creeps towards the foil; it first neutralizes the positive charge on the foil and finally gives the foil itself a negative charge, when of course it is repelled and flies away.

One can use this effect to make a very life-like 'electrical butterfly.' A butterfly of about an inch across is cut out of aluminium foil. An ebonite rod is rubbed very briskly so as to get a good crackling charge on it. The butterfly rushes to the rod, sticks to it for a

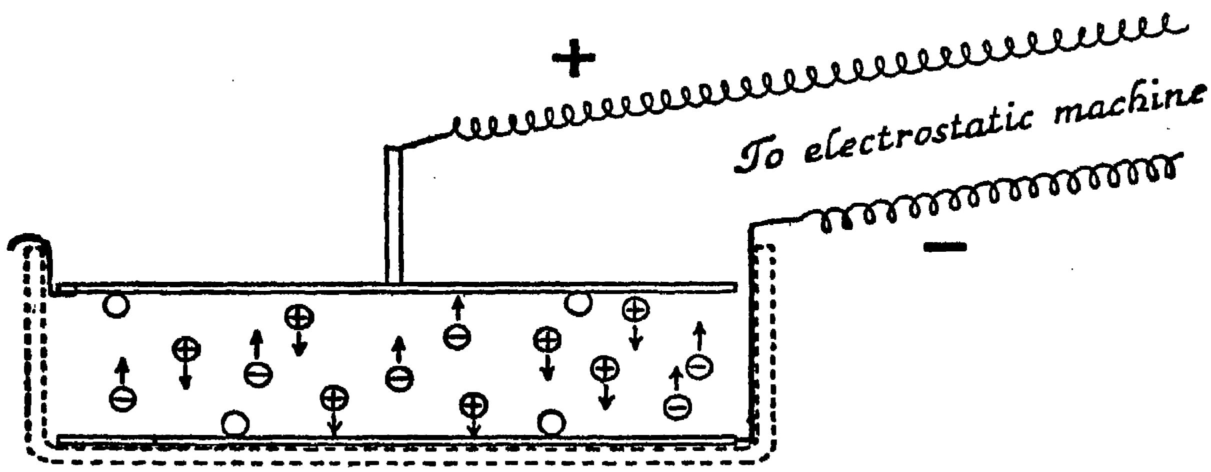


Fig. 8. Pith balls dancing between two oppositely charged plates.

moment, and then flies away through the air fluttering just like a real one. If the light from a lantern is thrown on it, the illusion is almost perfect. It can be guided by the rod, which drives it quite fast through the air even when held a foot away. If now one holds one's finger near, the butterfly will fly to it, settle on it for an instant and then fly away again as if disgusted with its mistake. Fig. 7 shows how this happens. The butterfly has got a negative charge from the rod, and the finger has a positive charge drawn into its tip because it is held near the rod, as has already been explained. The butterfly is first attracted by the finger tip, but when it touches, it picks up a positive charge and is repelled. It goes back to the ebonite rod and

picks up a negative charge, then back to the finger again and so on till the ebonite rod loses its charge. On the other hand, if a paper flower is held out to the butterfly, it will settle on it and stick to it. Paper is a fairly good insulator, and so the butterfly keeps its charge for a while and continues to be attracted to the flower.[1]

Fig. 8 shows a number of pith balls placed between two plates which are connected to an electrical machine

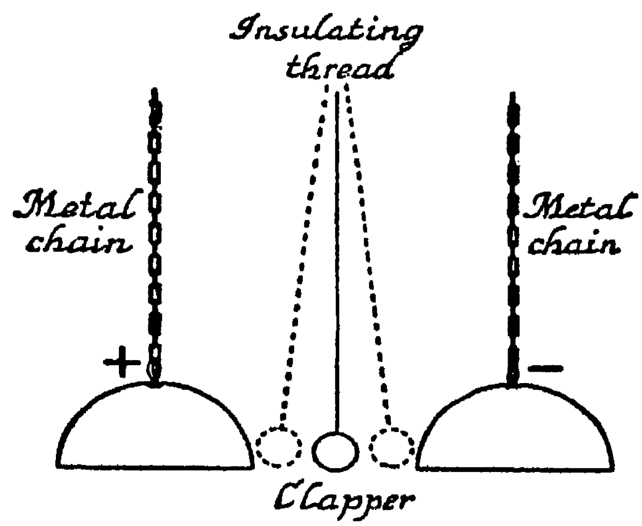


Fig. 9. The electrical chimes.

and so made positive and negative. A ball resting on the lower plate acquires a negative charge, is repelled and flies to the top plate. Here it picks up a positive charge, is repelled and flies to the bottom plate. As long as the plates are charged the pith balls dance backwards and forwards in the most lively way. A toy is sometimes made on this principle. A box has a glass lid which can be electrified by rubbing. A number of small dolls made of pith with jointed limbs are placed in the box, and when the glass is rubbed

[1] Aluminium foil serves well for the butterfly, because even when very thin it is fairly stiff. Foil about $0{\cdot}5 \times 10^{-4}$ cm. in thickness is suitable, and can easily be cut to shape between the sheets of paper in which it is sold. If the butterfly is found to stick rather firmly to the ebonite rod, as sometimes happens, a flick of the rod will dislodge it.

they dance up and down between lid and bottom. The 'Electrical Chimes' are made by connecting two bells to opposite poles of an electrical machine and having a light clapper hung by an insulating thread between them (Fig. 9). The clapper dashes to and fro ringing the bells for the same reason that the pith balls dance up and down in the last experiment.

4. LINES OF FORCE

When electrical charges are produced by friction or by other methods, a positive charge always has its counterpart in an equal negative charge. We cannot generate positive without negative or vice versa. In fact, we are not really 'making' electricity in any sense. The electricity is already there, for the things we rub together are made of positively and negatively electrified particles. Ordinarily their charges just balance each other, so that the body behaves in a neutral manner. The act of rubbing a rod with a cloth tears off more particles of one kind than the other, so that the balance is destroyed. The body which loses more negative particles than positive acquires on the whole a positive charge, and the other which has torn these particles away becomes negative. When an electrified body is 'discharged' the balance is restored again.

I now wish to build up a mental picture, by the aid of which we can follow the behaviour of any electrified system. It is the famous picture of 'lines of force' which the great Faraday developed a century ago. If we think in terms of these lines of force, we can interpret all the experiments described in this chapter very readily.

When the ebonite rod is rubbed with a piece of

flannel, the ebonite gets a negative charge and the flannel a positive charge. If they are now drawn apart, they attract each other. It is as if there were invisible elastic threads stretching from the one to the other, which are drawn out as the opposite charges are separated and collapse when they come together again. On the occasion of the Christmas lectures, I showed a rough model to make this point clear. A wooden block represented the ebonite rod, and on it we had a number of tape measures which could be pulled out of their cases and, when released, ran back into them with a snap. We marked each case — and a hook at the end of its tape +. A cloth rubbing the rod catches on to some of these hooks, and when it is drawn away the tapes are drawn out. If the cloth is released, the tapes draw it back towards the rod.

We must of course remember that these elastic threads are not 'real.' They are just something we picture in our minds as symbols. If, however, we make certain rules for the behaviour of the elastic threads, the picture is a true one in the sense that it gives the right answer to any problem. May I remind you of the way in which contour lines are drawn on a map in order to represent the variation in the height of the land from place to place. A contour line is drawn so that it runs through places which are at the same height above mean sea level, which is taken as a standard. Now these contour lines are not 'real,' because there are no lines on the ground which run along in this way. They do not represent anything actually existing like the lines which mark the roads and railways. On the other hand, they are 'true' if the map has been drawn correctly. They are a kind of

symbolism, and anyone who can read a map can follow out the lie of the land and the form of the hills and valleys with their aid. The lines of force are a device of the same kind to show the direction and strength of the electrical field of force.

Here are the rules. They can be given an exact mathematical form, but in this book we will leave mathematics severely alone. We want to get an instinctive general understanding of electrical problems first, and the precision which mathematics introduces can come later.

(*a*) Every line of force starts from a positive charge and ends on a negative charge. The greater the positive charge on a body the larger is the number of lines of force starting from it. We can choose some unit of charge, and make one line start from the body for each unit on it. Similarly, the end of a line of force represents a negative charge, and a body with a high negative charge will have a large number of lines ending on it. Since a line starting from a positive charge must have an end, there must be *somewhere* a negative charge which just balances the positive. This is only another way of saying that positive and negative charges are always produced in equal amounts.

(*b*) There is a tension or pull along the lines of force as if they were elastic threads always trying to shorten themselves.

(*c*) The lines of force push each other apart sideways. The model with the tapes is imperfect because the tapes do not repel each other sideways; it only shows the pull.

(*d*) The ends of the lines of force, representing charges, can move about freely over the surface of a

conductor, but they are fixed to one place on an insulator.

I will now take a series of electrical experiments and in each case draw the lines of force. We will start with some very simple cases. Fig. 10 (Plate 2) shows two round conductors with equal opposite charges. Lines of force stretch from one to the other, and try to pull them together. You will remember that the ends of the lines of force can move about freely on the bodies because they are conductors. If there were simply a tension of the elastic lines, they would all run to the part of each conductor nearest the other so as to bridge the shortest gap. The sideways repulsion prevents them from doing this, and the result is a balance between the tension which makes the lines crowd into the space between the bodies, and the repulsion which keeps them apart. The figure shows the effect of moving the bodies closer together, and you will see that as they approach, the lines crowd more and more into the lessening gap between them. This means that the bodies are attracting each other more strongly when close together than when far apart, because when they are closer more lines of force are pulling each body towards the other, and they pull hardest where crowded most closely.

Fig. 11 (Plate 2) shows the case of two bodies with equal *similar* charges, both being positive or both negative. If positive, the lines of force start from each body and run away to corresponding negative charges somewhere out of the picture. Since the lines repel each other sideways, they take up the form shown in the picture. It is easy to see that the bodies behave as if repelling each other. The lines of force on the

left-hand body, for instance, are mostly on its left-hand side and are pulling it to the left, away from the other. The closer the bodies approach, the greater is the force of repulsion between them.

Fig. 12 (Plate 3) shows the rather more complicated case of a pith ball dashing backwards and forwards between two oppositely charged plates. The pith ball is not a good conductor, but it is by no means a good insulator either, and charges can move about over its surface, though in rather a sluggish way. We start with the ball touching one of the plates, when it picks up a charge. In our language of lines of force, some of the lines stretching between the plates can shorten themselves if their ends leave the plate and run on to the pith ball. They, of course, pull it towards the opposite plate, and shorten up as the ball moves. When the ball arrives at the opposite plate, the lines collapse to nothing – as we say, the ball is discharged. We now start all over again. Lines of force run on to the ball in order to shorten their path, and the ball is drawn back to retrace its path. We can picture the lines of force stretching across between the plates and unable to collapse until the pith ball is introduced. It sets about releasing the strain. Each time it touches a plate it unhooks a certain number of lines of force, and runs over to the other plate to allow them to collapse, then unhooks more from the other end and so back again. We are reminded of the occasions when we are asked to help in making a ball of wool. We stretch the hank between our hands and let the turns go one by one as the ball passes backwards and forwards.

The pictures shown in the last three figures are taken

PLATE 3

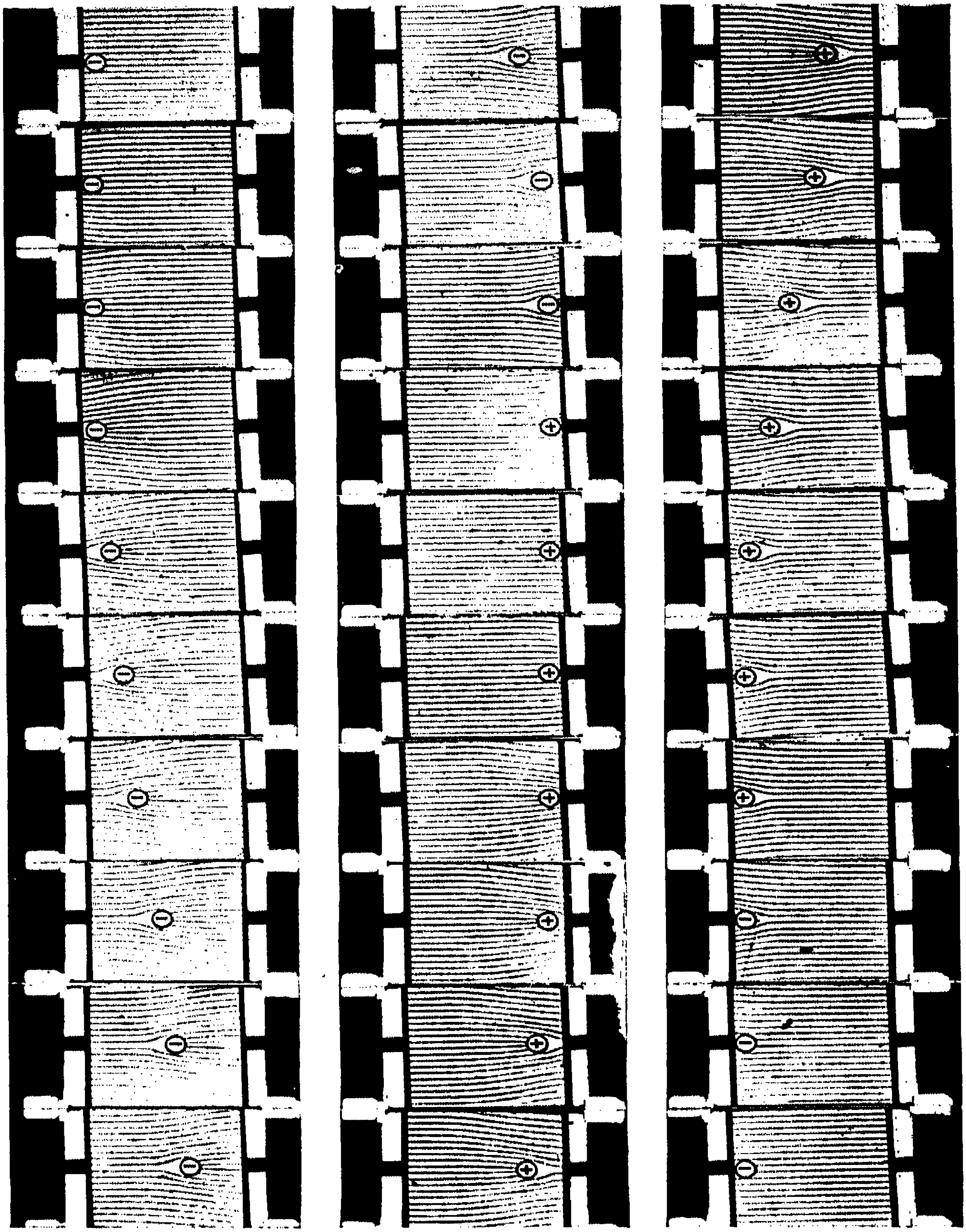


Fig. 12. Movement of the lines of force when a conducting ball rushes backwards and forwards between two charged plates (+ on right, — on left). The film starts at the upper left-hand corner (*Kodak*)

[*p.* 20

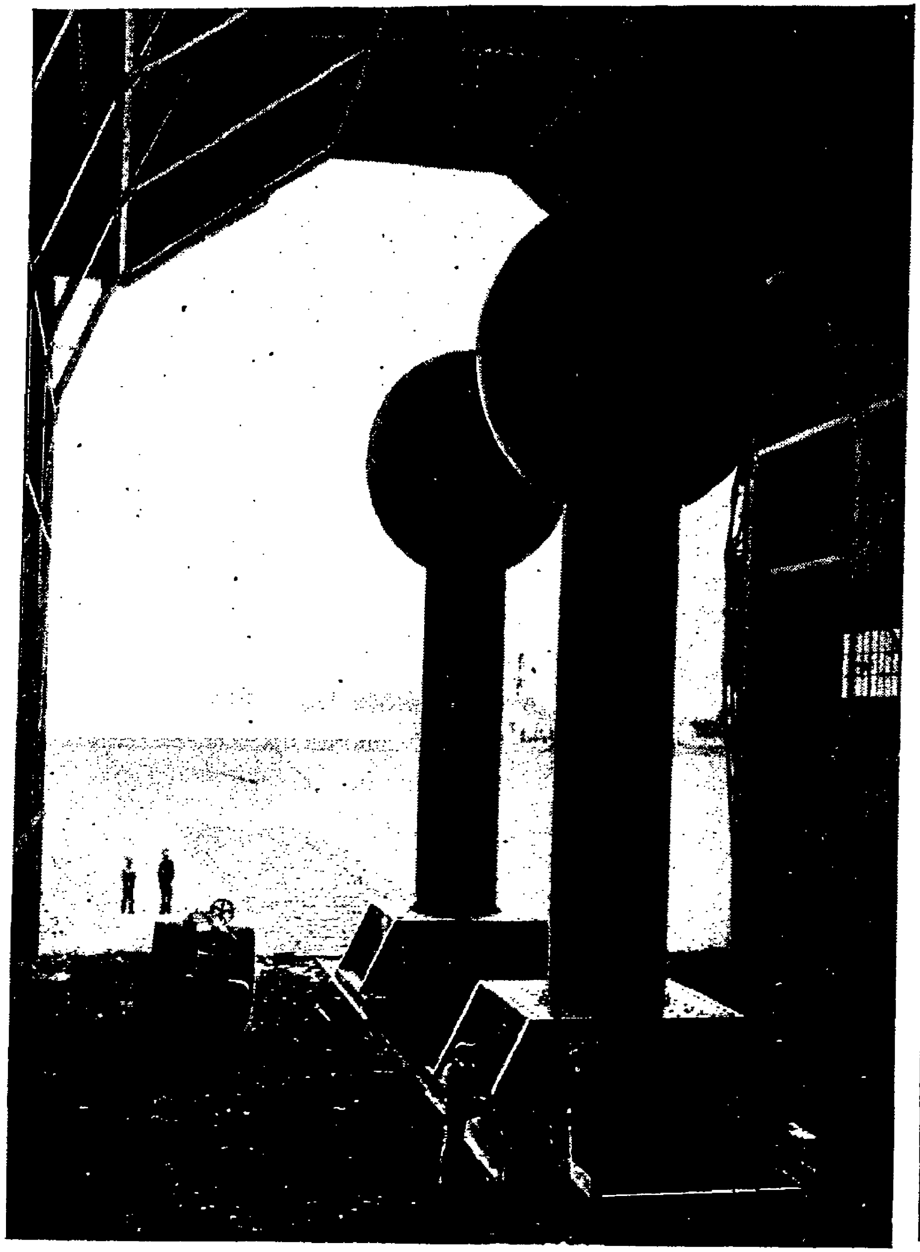


Fig. 21. A large van de Graaff machine erected by the Massachusetts Institute of Technology. It is housed in an airship hangar

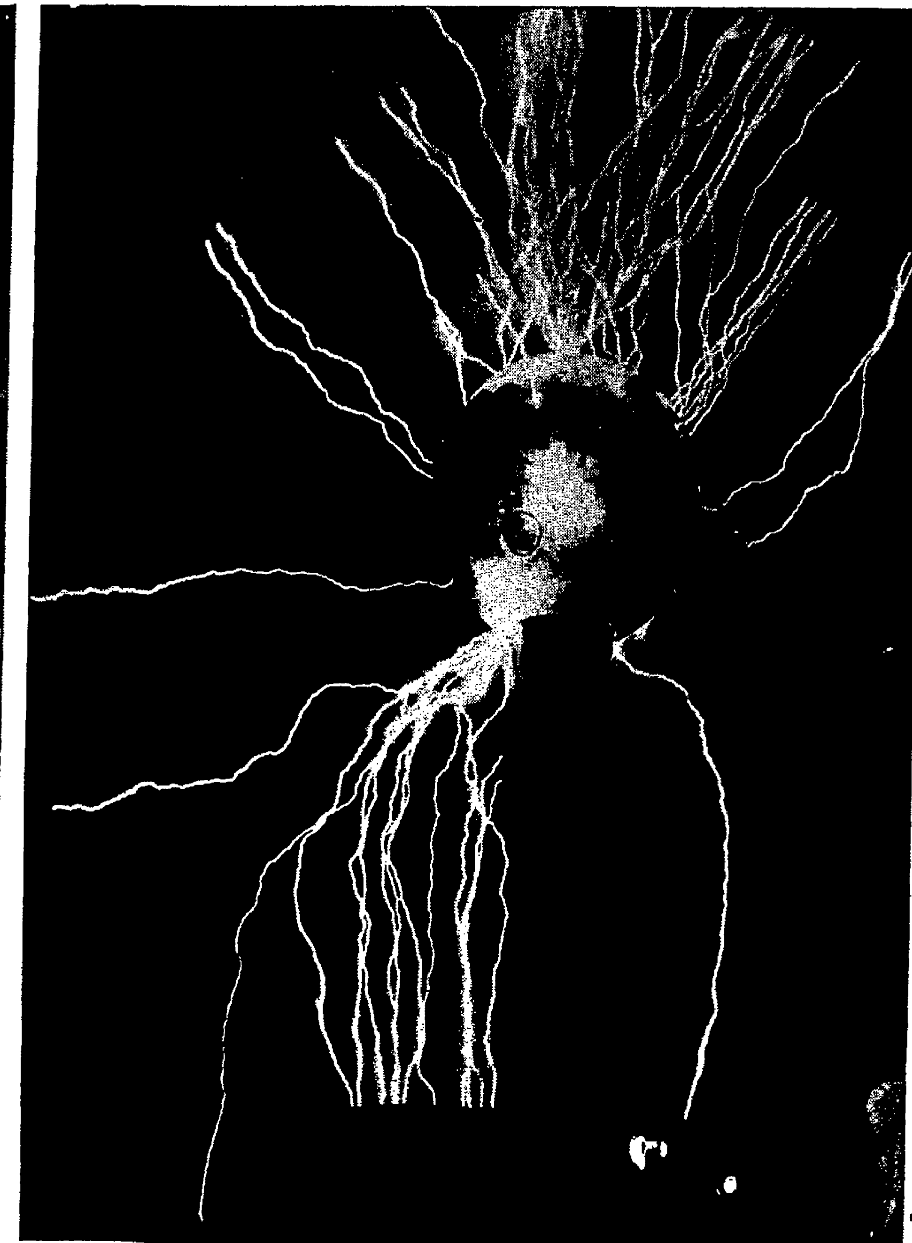


Fig. 22. Sparks from a terminal of the van de Graaff machine.

from a cinematograph film. This film shows the movements of the lines of force when two oppositely charged bodies approach and recede from each other, when two bodies with like charges do the same, and when a conductor moves backwards and forwards between oppositely charged plates. Since we could not get any lines of force to pose for us, we had to build up the picture artificially like an animated cartoon. It would no doubt have been a light task for Mickey Mouse and his gifted collaborators to have drawn the many hundreds of diagrams required for a continuous moving picture, but we had to adopt a short cut. The cine camera was mounted on a trolley which ran on rails. Two discs representing the charged bodies were fixed on sliding rods in front of the lens, so that they could be made to approach each other or move apart. The lines of force were drawn once for all on a big diagram fixed at the end of the trolley rails. As the camera rolled towards the diagram the charged bodies were made to move apart, and as it rolled back again the charged bodies moved towards each other. The motion was so adjusted that the lines always appeared to spring from the charged bodies in the correct way. When the film is projected on the screen, the result is very spectacular. One can sense the oppositely charged bodies being pulled together harder and harder as they approach, and the bodies with like charges repelling each other.

The pith ball ferrying lines of force backwards and forwards between the plates was photographed by a similar device. In this case, we slid the whole diagram of lines of force backwards and forwards under two shelves representing the charged plates. The pith ball

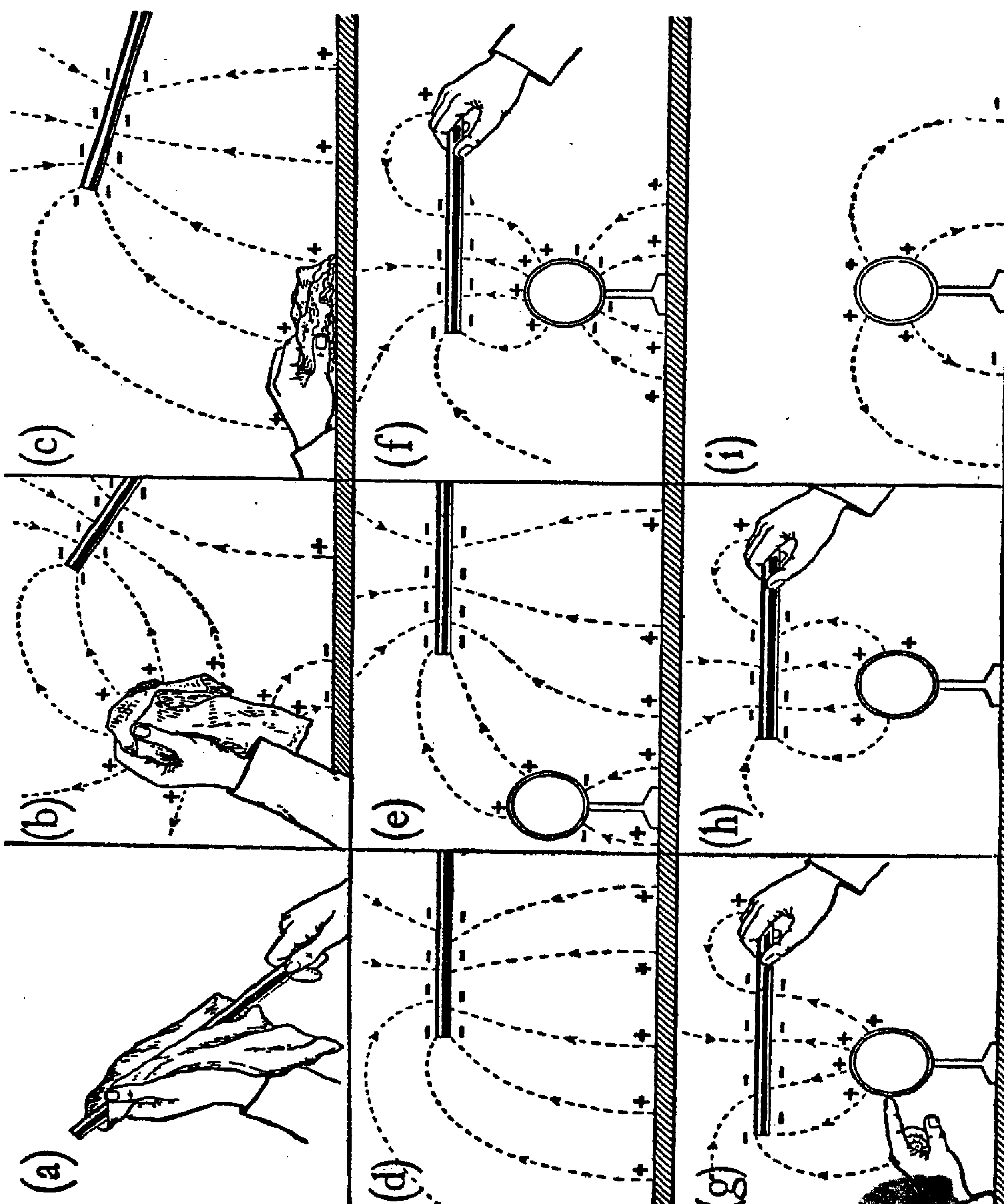


Fig. 13. A series of pictures showing the movements of the 'lines of force.'

was actually a shilling with a + painted on one side and — on the other. Each time it got to the end of its journey we stopped the camera and turned it over so that it should change its sign as it picked up a new charge from the plate. The photography was carried out by Messrs. Kodak, and I would like to take this opportunity of thanking them for their patience with the efforts of a very amateur producer.[1]

Fig. 13 shows what takes place in another electrical experiment. In (*a*) a rod is being rubbed by a cloth, and electrical charges are being separated by the friction. In (*b*) the cloth is taken away from the rod and the lines of force stretch out between them. Though most lines of force run direct from cloth to rod, a certain number run down to the table, which we have supposed to be a conductor, and up from the table to the rod; we may think of them as taking a short cut by means of the table. In (*c*) the cloth is laid down on the table. Any lines of force between cloth and table collapse to nothing, and we are left with lines of force starting from the table and ending on the rod as in (*d*). As the rod is carried about the room, you must picture these lines moving about with it, their far ends running along the floor or furniture because they are conductors. If we hold the rod near any projecting knob, most of the lines of force will run to it because it offers such a splendid short path for them. In (*e*) the rod is approaching a metal sphere on an insulating stand. In (*f*) it is held directly over it, and many lines of force seize the opportunity of a short cut by running from rod [illegible]phere and then on from the sphere to the table. In [illegible] sphere is touched by the finger. We have

[1] [illegible] of these films may be obtained from Messrs. Kodak.

now a conducting circuit between the table, through the observer's body to the sphere. Any lines of force which stretch between the sphere and the table at once collapse, because *no line of force can begin and end on the same conductor.*

This is obvious in Fig. 14 (*a*) where the conductor is a straight rod, for the tension along the lines of force

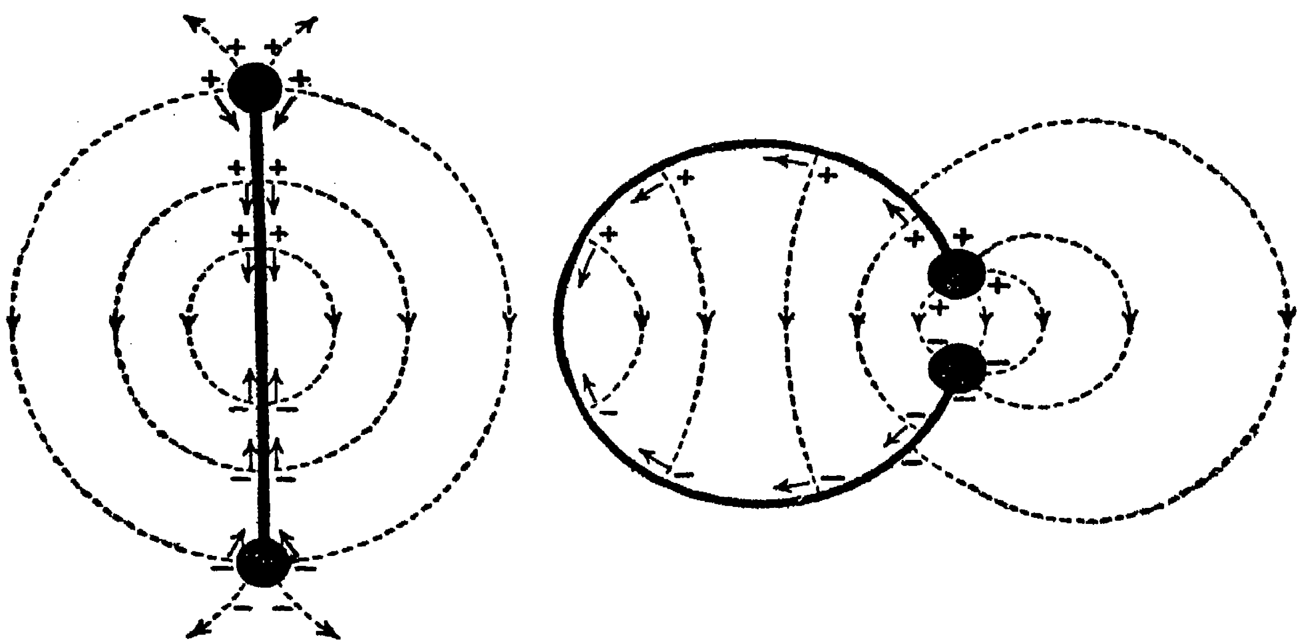


Fig. 14. The collapse of lines of force which begin and end on the same conductor.

clearly pulls their ends towards each other and the elastic lines collapse. It is not so clear that it will happen in Fig. 14 (*b*) where the lines have a very convenient short path between the two knobs. One might imagine that their tension would prevent their ends running back around the circuit so as to collapse. We must remember the sideways pressure, however, which drives some of them to the left as shown. As the lines on the left collapse, more are driven in the same direction, and finally all the lines disappear.

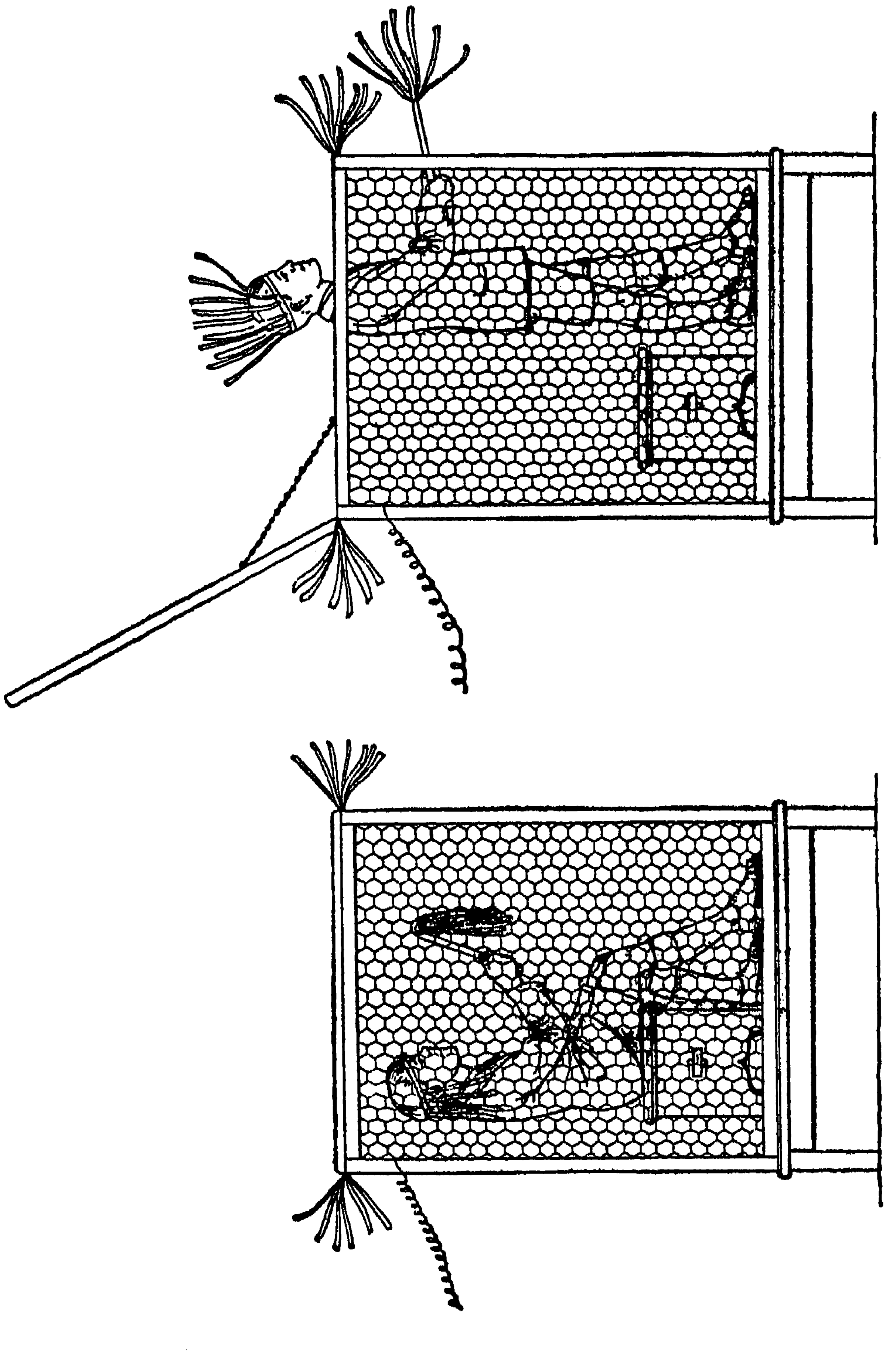


Fig. 15. The 'Boy in Cage' experiment.

We see, therefore, that if lines of force stretch from one conductor to another, and these conductors are joined by a conducting path, however roundabout it is, all the lines will promptly collapse.

To go back to Fig. 13, we see in (*h*) the state of affairs when the finger is withdrawn. In (*i*) the rod has been taken away, and the sphere is left with lines of force running from it to the table. By bringing a negatively charged rod near the sphere, touching it for an instant, while the rod is still near, and then taking the rod away we have charged the sphere positively.

This is called *charging by induction*; charges produced on a conductor simply because another charged body is near are said to be 'induced.' At first sight it would seem that we have got something for nothing by producing a charge without doing any work. Nature never lets us cheat in this way, however. If we just brought the rod up to the sphere and took it away again, no work would be done, but if the sphere is touched, the positive charge on it attracts the rod as it is drawn back and forces us to do some work, in other words, to pay for the charge.

Fig. 15 shows an old experiment of Faraday's. A cage is made of wire netting, so that its surface is a conductor. It is on an insulating stand, and can be electrified by a machine. Bunches of streamers tied to the corners of the cage stand out stiffly, being drawn out by lines of force passing from the cage to its surroundings and crowding into the corners to get as short a path as possible. The boy inside the cage feels nothing, however. In his original experiment, Faraday took some of his most delicate instruments into the cage and could detect no signs of electrification. If you have

followed the picture of lines of force, you will see the reason for this. There can be no lines of force *inside* the conducting cage, for they would have to begin and end on the same conductor, which we have seen to be impossible. We may note at the same time that the cage completely screens anything inside it from the effects of electrified bodies outside, for a line of force which would otherwise have to pass through the cage would take a short cut by ending on one side and starting again on the other side of the conducting surface.

The boy is wearing a head-dress of streamers, and holds a stick ending in streamers in his hand. As long as he remains inside the cage, the streamers are limp because there are no lines of force to draw them out. If the stick is thrust through a hole in the cage, or if the lid is lifted and he puts his head out, the streamers spread out. The stick or his head now become projecting points of the charged conductor, and so the lines of force crowd into them. If he retreats into the cage and the lid is closed, the streamers collapse again.

These examples might be multiplied indefinitely, but we have perhaps described a sufficient number to illustrate the behaviour of electrical charges. I want you to imagine these elastic threads drawn out whenever the positive and negative charges in a body are separated. The threads, once made, cannot disappear unless their ends are either brought together or are allowed to run together along a conductor. Places where the lines start have got a positive charge, and places where they end have got a negative charge. If the lines take a short cut by means of a conductor,

that conductor will have a positive charge at one place and a negative charge at another.

Finally, we will see why they are called lines of force. Suppose some tiny body with a positive charge on it, like a very small electrified soap-bubble, were placed anywhere in one of these systems of lines of force. In what direction would it move? Some of the elastic threads would be attached to it because of its charge, and they would drag it along as they shortened. It is clear that the bubble would always drift *along the lines of force.* The way in which the lines spread out from one conductor and come together again on another is shown very prettily by the bubble-blowing experiment I have already described. The bubbles do not all go directly from one man to the other. Some start in an upward direction, sweep round overhead, and come down again like the lines of force in Fig. 10 (Plate 2).

Lines of force thus map out the direction of the force on a positive charge at any point, hence their name. Where the lines are crowded closely together the force is strong, and where they are far apart it is weak. There is said to be an 'Electric Field' in a region which is traversed by lines of force.

5. POTENTIAL

'Potential' is one of the new words which had to be coined when the phenomena of electricity were being discovered. We cannot avoid these words, and, although I will use as few as possible in this popular account, anyone who is interested in electricity must acquire a certain elementary scientific vocabulary and understand thoroughly the meaning of the words in it. We shall want to use 'potential' very often.

When one body is at a higher potential than another lines of force run from it to the other body. If the bodies are connected by a conductor these lines will collapse and a 'current' will flow. We may think of potential as a *pressure* tending to drive positive electrification away from a body.

We often use the expression 'connected to earth' or 'earthed,' and say that a charged body is discharged by 'earthing' it. Earth here means the whole world, which is a huge conductor, and which we define as being at zero potential. If a body is at a higher potential than the earth it is said to have a positive potential. If it is at a lower potential than the earth it has a negative potential. To go back again to the analogy of a map, potential may be compared to the heights above sea-level marked on the map. Mountains are at a high positive potential. Water runs *away* from them down the slopes till it ends in the sea, which is the level of zero potential. On the other hand, a place like the Dead Sea which is below sea-level is at a negative potential. If we could connect it to the neighbouring sea by a conducting channel, water would flow into it, not away from it.

How are we to measure this potential? When water flows from a higher to a lower level, it can be made to do work on the way. A water-wheel works on this principle, the water being held back in a dam and allowed to fall to a lower level over the buckets of the wheel. The higher the fall, the more work will each gallon of water do. In the same way, when electricity flows from a place of high potential to one of low potential, it can be made to do work. The difference of potential is measured by the amount of work

obtainable during the flow of each unit of electricity. There are various ways of deciding what to call a unit of electricity which I need not go into here. Whatever way we decide on, we make the unit of potential to correspond to it. The usual unit is called a Volt.

It would seem obvious at first sight that if a body has a positive charge on it, it will be at a positive potential, and if a negative charge at a negative potential, but this is not true. Fig. 13 shows examples which warn us that we must keep the ideas of potential and charge separate in our minds. In Fig. 13*f* the sphere has no charge on the whole, since it was uncharged before the rod approached it and has not yet lost or gained any charge. Nevertheless it is at a negative potential with respect to earth because lines of force run from 'earth' (in this case the table) to the sphere. The lines running from the sphere to the rod show that the latter is at a still lower negative potential. When the sphere is touched by the finger, and so connected to earth, it is at *zero* potential, but has a *positive* charge, as in Fig. 13*h*. When the rod is finally taken away the sphere has both a positive charge and positive potential. This sounds much more confusing when put in writing than it does when one looks at the diagram, and I can best advise the reader to draw a few pictures of lines of force for himself, when I think all will become clear.

6. CONDENSERS

A 'Condenser' is a reservoir in which an electrical charge can be stored. In reality, every conductor is a condenser, because we can put an electrical charge on it. If, however, we wish to store a large charge

and keep on adding extra charge to a conductor in order to do this, we may have to raise its potential to an inconveniently high point; it may be so high that a spark passes and the conductor is discharged. We can get round this difficulty by making the conductor of such a shape that it will hold all the charge we require

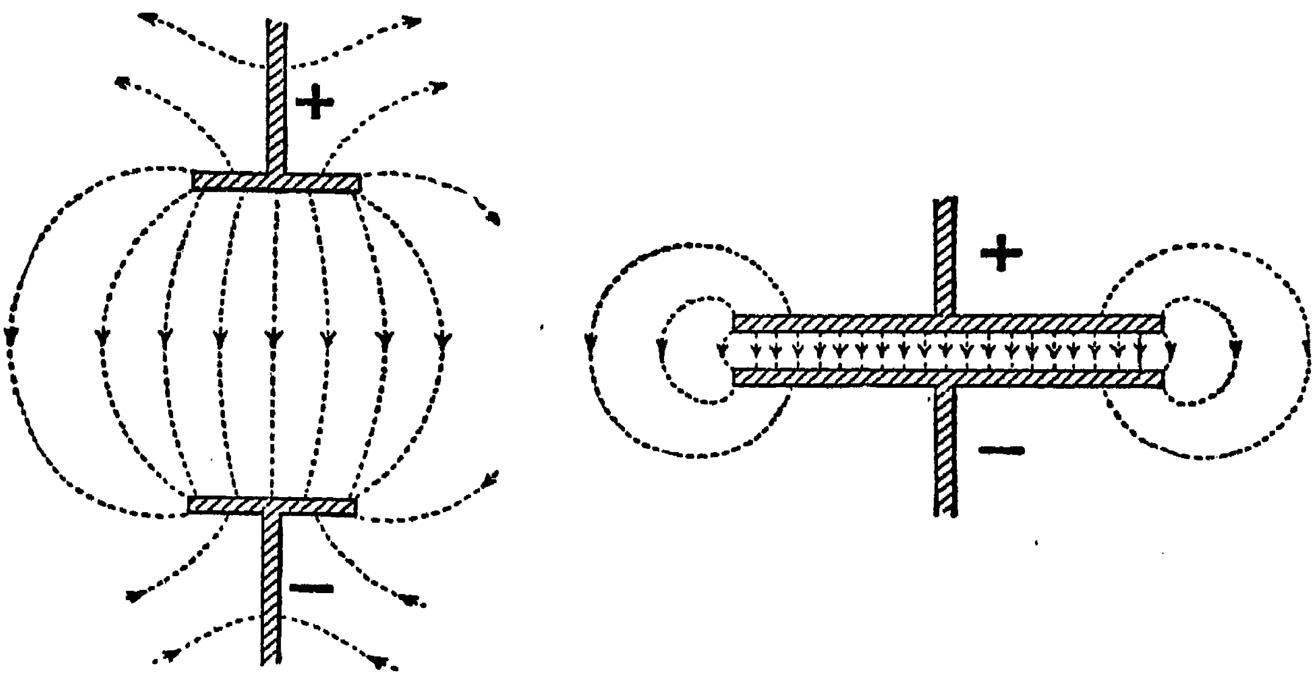


Fig. 16. A condenser of small capacity (left), and of large capacity (right).

without being raised to too high a potential. Such a condenser is said to have a large 'capacity.'

Fig. 16 shows a condenser of small capacity and one of large capacity. The former is not holding a large charge (count the number of lines of force) and yet is at a high potential, because in going from the top plate to the bottom by such a long path a large amount of work can be done by a unit positive charge. It is like water running a long way down hill from a high level. Conversely we should have to do much work to charge the condenser, just as we should have to do much work to pump up water from the bottom to the top of a high hill. In the other condenser the path

is very short. We have got a large charge on the top plate, as shown by the large number of lines of force, and yet the potential is quite low. It is like a big reservoir covering many acres, but only at a small height, so that it is quite easy to pump water into it.

Condensers of high capacity are made on this principle. As you can see by taking a wireless condenser to pieces, there are many thin plates in it, placed close together. We have drawn an 'air condenser,' but it is usual to put thin sheets of waxed paper or of mica between the plates which serve a double purpose. They resist the passage of a spark, and consequent discharge of the condenser, better than air. It is also found that when these sheets are between the plates we can get several times as large a charge on the plates as compared with a corresponding air condenser at the same potential. This difference is due to a very complicated effect upon the atoms in the sheets, which may be represented by what is called 'dielectric constant.' This action cannot be explained simply (its complexity is usually glossed over in text-books). We will leave it alone, only noting that it is useful in making condensers.

In Fig. 17*a* a condenser is connected to a gold-leaf electroscope and charged. Most lines of force choose the very easy short path of going directly from one plate to another. A few are squeezed out by the repulsion and choose the alternative of running from the gold leaves to the case of the electroscope and so make the leaves spread out a little by their pull. In Fig. 17*b* the upper plate of the condenser has been raised. Its potential is now higher because the lines of force have a longer path. We also see the gold leaves of the

electroscope spread out more widely. The direct path between the plates is no longer so attractive, and more

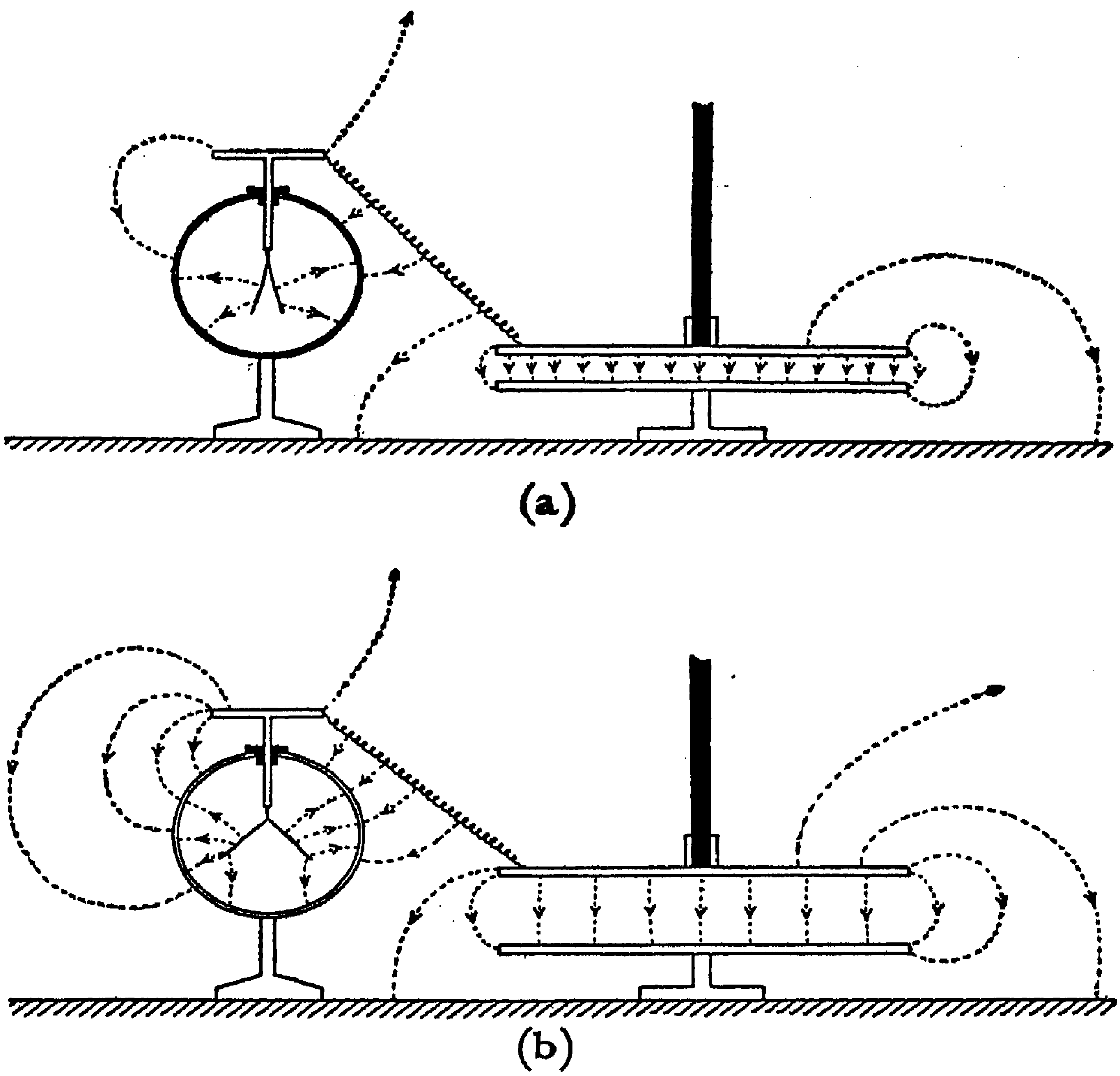


Fig. 17. When the plates of the condenser are separated, the gold-leaf electroscope receives a larger proportion of the charge and its leaves spread out further.

lines of force run over into the electroscope, where they find an alternative short path. I give this illustration to explain the effect when I stood on tip-toe on the ebonite sheet (see p. 8). When I shuffled my feet and charged myself, at first most lines of force ran

directly from the soles of my shoes to the ebonite plate because it was so very short a path. But on rising on my toes, this path became longer, and therefore the electroscope got a bigger share of the lines. It was for this reason that the leaves spread out when I rose on my toes and collapsed again as I sank back.

7. MACHINES FOR PRODUCING ELECTRICAL CHARGES

Many machines for producing charges have been designed from time to time. I will only describe here one of the earliest and one of the latest.

The *Electrophorus* was invented by Volta about 1775. A shallow tin dish is filled with a resinous composition which solidifies to a cake, and this cake is negatively electrified by rubbing. There is a laboratory tradition that a cat's fur is the best thing for this purpose, and most physical laboratories have a catskin which is produced when the electrophorus is in demand. I have often wondered by what devious channels the skins of these poor pussies have been obtained. A metal plate somewhat smaller than the cake is held by an insulating handle. It is placed on the cake, touched by the finger for an instant, and then removed, when it will have acquired an electric charge.

The figure shows how this takes place. The lines of force from the electrified resin take a short cut by way of the plate when it is laid on the cake. When the plate is touched, all lines passing from earth to its upper surface collapse, leaving only the lines between plate and cake. There is no room in Fig. 18*c* to show these lines, but you must picture them still stretching

between the plate and the cake. The cake holds its negative charge so firmly that it is not discharged even when the plate is laid on it. When the plate is taken away, it carries the ends of these lines with it and so has a positive charge. The cake remains electrified, and the process can be repeated again and again. It

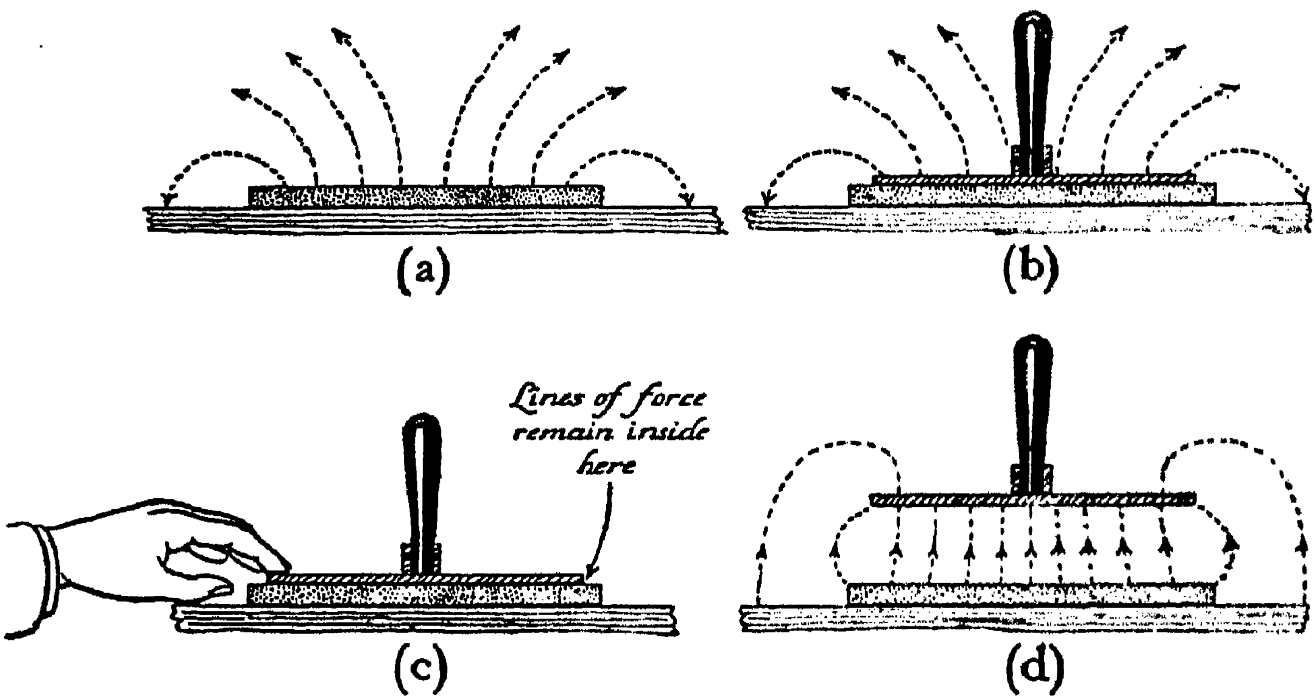


Fig. 18. The Electrophorus.

is merely another example of charging by induction as shown in Fig. 13. Work is required to produce the charge because we have to pull to get the plate away from the resin.

Complicated machines like a Wimshurst work on a similar principle of producing charges by induction. Instead of the rather clumsy process of putting a plate opposite an electrified body, touching it, and then removing it, plates are put on insulating discs which rotate. At one point in the rotation they are opposite inducing charges and are touched by a brush, at another point they hand over their induced charges to

a terminal conductor of the machine. It is easier to understand a Wimshurst by looking at the machine itself than by looking at a diagram, and as it brings in

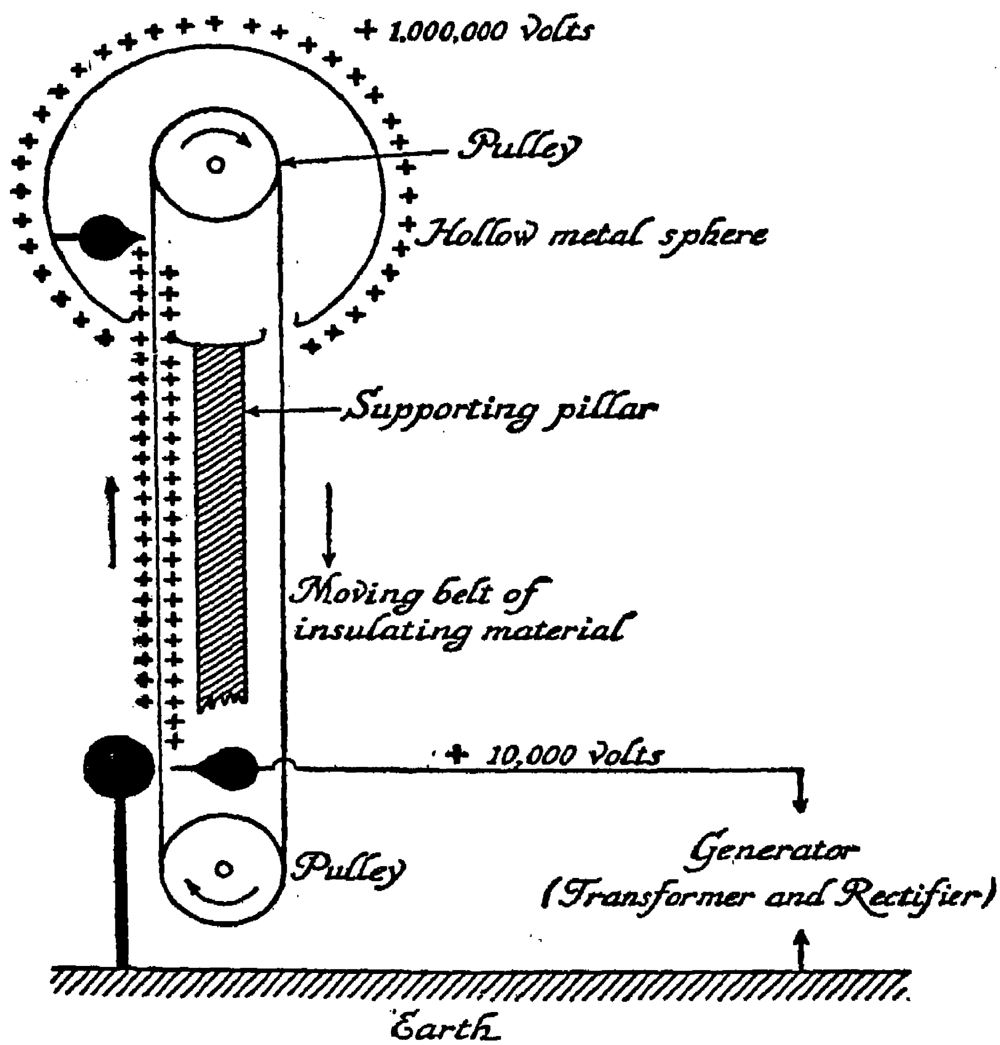


Fig. 19. The principle of the van de Graaff machine. A positive charge is sprayed on to the moving belt by the lower pointed conductor, carried up by the belt, and collected by the upper pointed conductor. The charge accumulates on the outer surface of the sphere.

no new principles I will not try to give a description of it here.

Although the gigantic van de Graaff machine, which forms my next illustration, is the most recent type to be devised, it works in a very simple way and is a good illustration of the principles of all electrostatic machines. It is shown in Fig. 19.

A large hollow metal sphere is supported on an insulating pillar. An endless belt runs over a pulley inside the sphere, entering it by one slit and passing out by another. It runs over an earthed pulley near the ground, the lower pulley being driven by a motor. The belt is made of insulating material such as silk. A positive charge is 'sprayed' on to it as it leaves the lower pulley by making it pass near a pointed conductor which is charged to + 10,000 volts. It is a simple matter to get a steady supply at 10,000 volts by means of a transformer and a rectifying valve, such as will be described later in this book. You will see this pointed conductor and a sphere connected to earth on opposite sides of the belt in the illustration. There is such a tremendous concentration of lines of force at the point that the resistance of the air breaks down, and positive charge is continuously being lost by the point and collected by the belt. The positive charge is carried upwards by the movement of the belt and enters the sphere. Here the charged belt comes opposite another pointed conductor, creating so strong a field that again the resistance of the air breaks down and the positive charges pass to the sphere, where they of course collect on its outer surface. To put it in another way, we may think of the lines of force starting from the positive charges on the belt, so that their ends are carried up by the belt. As the belt enters the sphere, each line of force is cut into two parts, one running from the belt to the inside of the sphere and the other from outside the sphere to earth. A discharge takes place at the pointed conductor inside the sphere just as it does at the lower point, so that all the bits of the lines of force that have got trapped inside the

sphere collapse and disappear. The final result is that we carry up the ends of lines of force attached to the belt, and then hook them on to the sphere. The metal sphere keeps on collecting charge until it reaches an enormous potential, only limited by the leakage of the charge through the air or along the supporting pillar.

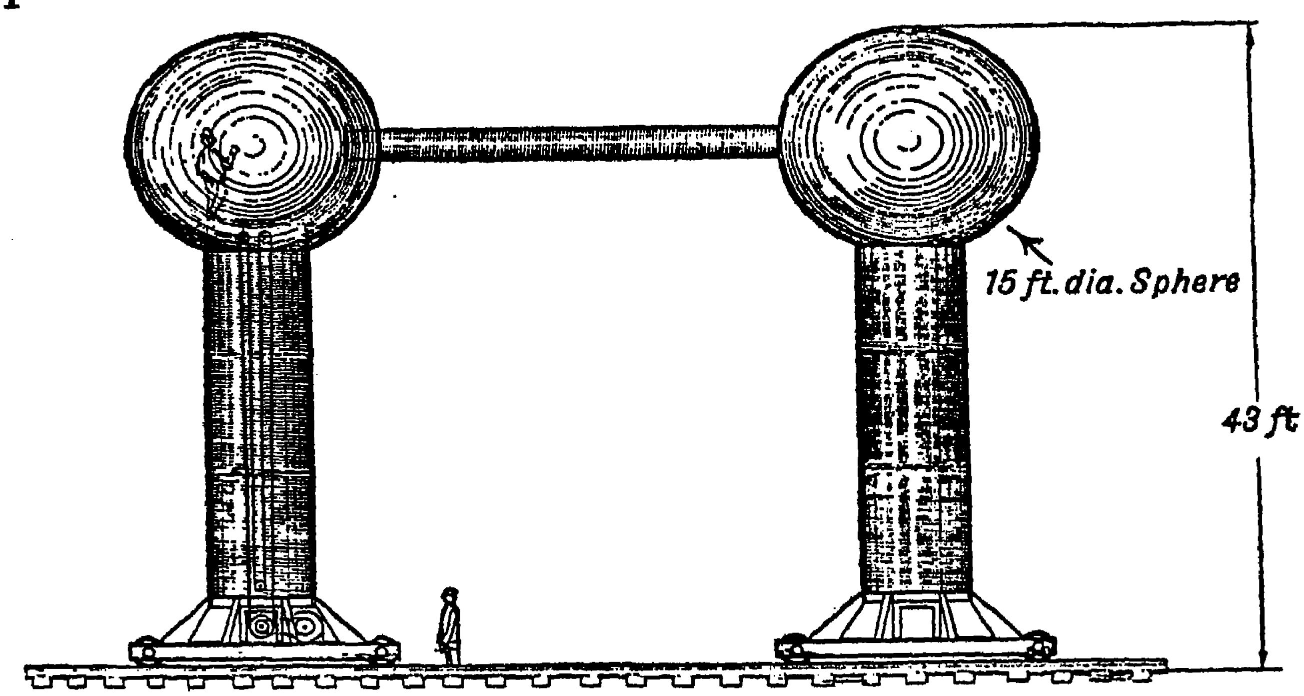


Fig. 20. A plan of the van de Graaff machine, designed to attain a potential of several million volts. (*'Physical Review,'* 1928.)

Fig. 20 shows the plan of an apparatus designed to reach 10,000,000 volts. There are two metal spheres, one of which is charged + and the other −. The tube connecting them at the top is intended to contain apparatus for which a potential of ten million volts is required, such as a tube for producing an electron beam of very high energy. The laboratory for measuring the effects of the voltage is *inside one of the spheres*. Each sphere is 15 feet across and so has quite a large room inside, with a floor, tables, and all the necessary measuring apparatus. Though the observer is at a potential of millions of volts he does not come to any

harm, and in fact is quite unaffected, because he is inside a closed conductor. A photograph of the apparatus is shown in Fig 21 (Plate 4). There must be plenty of room around the sphere or it will spark to the earth, and actually the whole apparatus is housed in a hangar originally meant for an airship, the spheres being on trucks running along a railway inside the hangar.

Fig. 22 (Plate 4) shows a series of sparks from the conductor to the roof of the hangar.

The apparatus may be called a moving staircase for electrical charge. The work required to produce the charge is done by the driving motor, which has to pull the positively charged belt towards the positively charged sphere against the force of repulsion.

As a last example of an electrostatic machine, we will take a thunderstorm. Though a great deal has been found out about thunderstorms, largely owing to experiments made by Professor C. T. R. Wilson, of Cambridge, the actual way in which they produce such vast electrical charges is still not settled. It is generally agreed, however, that the rain drops in the thunderstorm are in some way responsible.

A thunderstorm is like a gigantic electrical machine about a mile in each direction. According to C. T. R. Wilson, the top of the cloud becomes positively charged and its bottom negatively charged. The charges accumulate until the potential becomes sufficiently great to break down the resistance of the air, lightning being a spark a mile or two long which discharges the cloud. Most lightning flashes pass from top to bottom of the thunder-cloud, but sometimes the bottom of the cloud sparks to the ground and a tree or building is

'struck by lightning.' Once the spark has followed a certain path through the air, this path remains a conductor for a certain time, and generally several flashes follow each other along the same path. It is these successive flashes which cause the flickering of lightning which we often notice, for each individual flash is over in less than one thousandth of a second. When a cloud has been discharged, it takes about 20 seconds for it to accumulate enough charge for another flash.

The thunder is due to the same cause as the sharp crack we hear when an electric spark passes between two conductors. The noise is produced instantaneously all along the lightning flash; why then do we hear the long-drawn roll of thunder with a series of big bangs at intervals? This is due to the different times which it takes for sound to reach us from different parts of the spark. Sound travels at 1,100 feet per second, taking five seconds to travel a mile. Sound from the nearest part of the flash reaches us first, and then sound from the parts further away, so that the whole peal of thunder may last for several seconds.

The distance away of a thunderstorm can be estimated by counting seconds between flash and the beginning of the peal, and allowing a mile for every five seconds. When the ground is struck somewhere close by, a terrific crack is heard following close after the lightning. When the storm is in the distance, quite a long interval elapses.

C. T. R. Wilson's theory of the way in which the cloud gets charged is as follows. We must picture an initial state of affairs in which the top of the cloud is positively charged, the bottom negatively charged, and

a heavy shower of raindrops is falling through the cloud. Each raindrop has a negative charge induced on its top and a positive charge on its bottom, owing to the charges on the cloud (see Fig. 23). The air is

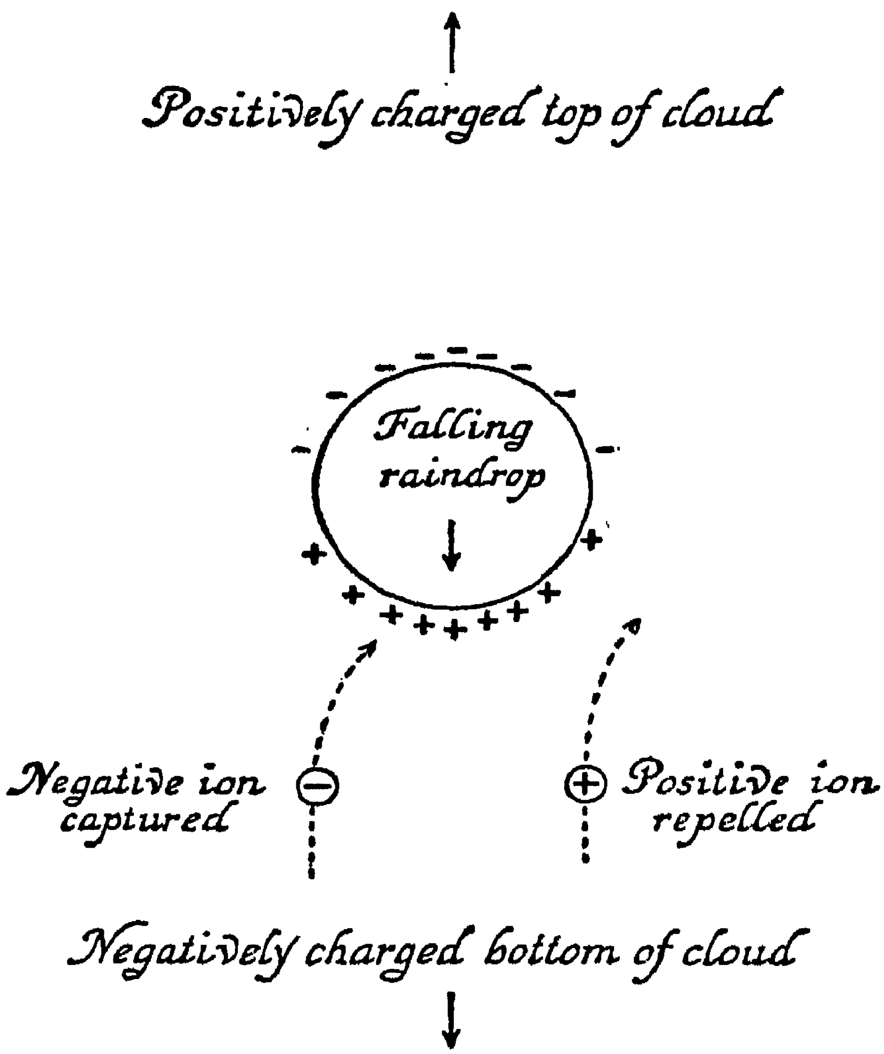


Fig. 23. The way in which a thunder-cloud becomes charged, according to C. T. R. Wilson.

already full of free positive and negative charges probably left over from the last discharge and attached to tiny drops or to molecular clusters. The falling drop scoops up these charges, but since the positive end of the drop is the front end as it falls, it will mostly scoop up negative charges, which it attracts, and will push the positive charges out of the way. These positive charges have not time to attach themselves to the

negative upper end of the falling drop. Therefore the drop on the whole picks up a negative charge and carries it downwards, and this increases still further the negative charge on the bottom of the cloud. It works just like a big electrostatic machine in which the drops are the moving conductors.

Dr. G. C. Simpson, on the other hand, ascribes the charges to the breaking up of big raindrops into smaller ones, for it is known that charged drops are produced in this way. Perhaps both effects are at work.

The potentials produced are very high, being of the order of one thousand million volts. On the other hand, the actual amount of electricity which flows in a lightning flash is quite small. It amounts to about 20 coulombs (we will see later what a coulomb is), whereas when we use the self-starter of a motor-car the battery is called on to supply about ten times as much. However, since the potential is so high, a lightning flash represents a very large amount of energy. An ordinary thunderstorm is working as hard as about ten Battersea Power Stations (several million kilowatts). According to the ancients, Jupiter when displeased with anyone on the earth slays them with a thunderbolt. If this is so we must admit that he wastes a terrific amount of ammunition when he sets about a bombardment, for it is remarkable that all this expenditure of energy goes on overhead and yet so rarely harms us.

It is estimated that there are about 16,000,000 thunderstorms a year all over the world, and 1,800 going on somewhere at any given moment. Every time a lightning flash passes, and a cloud is discharged, the field of force all around is suddenly changed as we have seen in other electrical experiments. It is these

disturbances which cause the crackles in a wireless apparatus which we call 'atmospherics.'

8. WHAT IS ELECTRICITY?

We come back again to the question, 'What is Electricity?' What is this mysterious something which can be produced by friction and which shows attractions and repulsions? Why should the electrical current flowing from one place to another give rise to the magnetic and other effects which we will study in the following chapters?

This is an extremely interesting and important question. An excellent answer has been given by Bertrand Russell in his *ABC of Atoms.* After talking about electrons and nuclei, the negative and positive particles of which all matter is composed, he goes on to say:

'Some readers may expect me at this stage to tell them what electricity "really is." The fact is that I have already said what it is. It is not a thing like St. Paul's Cathedral; *it is a way in which things behave.* When we have told how things behave when they are electrified, and under what circumstances they are electrified, we have told all there is to tell. When I say that an electron has a certain amount of negative electricity, I mean merely that it behaves in a certain way. Electricity is not like red paint, a substance which can be put on to the electron and taken off again, it is merely a convenient name for certain physical laws.'

There must always be a final something which we cannot explain. Let us take an instance. Suppose a

very persistent questioner were to ask us to explain a mirror. We would talk about the way light is reflected in a mirror and, by drawing a sketch or two, show him why he saw his face when he looked into it. He might then ask why the light is so strongly reflected by the mirror. We would answer that it is a smooth metallic surface (mercury) and that metals always reflect light very well. Why do metals always reflect light well? Now we are getting into deeper water, but it is still possible to give an answer. Metals, like other bodies, are built up of electrons and nuclei. In metals electrons are exceptionally free to move, and this accounts for the high reflecting power. Why do the electrons have this effect? Because they are electrified particles and react to light according to certain laws. Why do electrified particles obey these laws? At this stage we are reduced to saying in an exasperated way: *Because they jolly well do.*

If we had started out to explain anything else, we should have ended at the same point. Everything is made of electrified particles, and by electrified we mean that they behave in a certain way, so 'Electricity' is only a word for the way in which everything behaves. We can explain anything in terms of electricity, but here we must stop and take this electrical 'behaviour' for granted.

I can perhaps help to make the point clear by quoting some early attempts to explain the behaviour of electrified bodies and that of magnets. Electricity and magnetism are merely different aspects of the same fundamental behaviour of everything, as we shall see later. The attraction of bodies when electrified, and the attraction of the magnet for iron, have been mysteries

which have excited the imaginations of the curious in all times. I have taken these quotations from that fascinating book the *Biographical History of Electricity and Magnetism*, by P. F. Mottelay.

'A treatise by Robert Boyle (*Philosophical Works*, 1738) deals with various hypotheses advanced to solve the phenomena of electrical attraction. The first is that of the learned Nicholas Cabaeus (A.D. 1629), who thinks that the drawing of light bodies by amber . . . is caused by the streams which issue out of such bodies and discuss and expel the neighbouring air . . . making small whirlwind. Another is that of the eminent English philosopher, Sir Kenelm Digby (A.D. 1644), and embraced by the very learned Dr. Browne (A.D. 1646) and others, who believed that chafed amber is made to emit certain rays of unctuous streams, which, when they come to be a little cooled by the external air, are somewhat condensed . . . carrying back with them those light bodies to which they happen to adhere at the time of their retraction. Cartesius (Descartes, A.D. 1644) accounts for electrical attractions by the intervention of certain particles, shaped almost like small pieces of riband, which he supposes to be formed of the subtile matter harboured in the pores or crevices of glass.'

Lucretius (99–56 B.C.) accounts for the adhesion of the steel to the loadstone (natural magnet) by saying that on the surface of the magnet there are hooks, and, on the surface of the steel, little rings which the hooks catch hold of.

Another author in the seventeenth century satisfied himself by saying that 'it is a certain appetite or desire

of nutriment which maketh the loadstone snatch the iron'!

The difference is that, whereas these old investigators explained electricity and magnetism as due to hooks and rings, ribands, and unctuous streams, we now explain hooks and rings and ribands in terms of electricity.

Have we really probed any deeper than they did? I think we cannot doubt that we have done so. We are confronted by a fundamental and insoluble mystery just as they were. But we can write down the fundamental laws in a short and simple way, and then explain everything else in terms of these laws, whereas they had to invent new and vague explanations for every new discovery. Science can show that many different effects we observe are in reality closely related and can be said to be due to the same fundamental causes, but in the end we have to be content with a statement of these causes, we can never 'explain' them.

CHAPTER II

HOW ELECTRICITY TRAVELS

I. THE VOLTA PILE

We have seen in the last chapter how electric charges upon bodies are produced. If two conductors at different potentials are connected by a wire, or if a spark passes between them, an electrical charge rushes from one to the other so as to equalize their potentials. This happens in a flash, quite literally 'as quick as lightning,' because lightning is nothing more or less than the discharge from one cloud to another or to the earth. We know that the 'something' which passes in the discharge produces effects. For instance, it must heat conductors along which it passes, since trees are blasted by lightning and buildings sometimes set on fire. However, there is no time to make experiments on the discharge because it is all over so quickly.

You can imagine the stir in the scientific world when a means was discovered of creating a *continuous electrical current.* This discovery was made by Volta, and announced in the year 1800 in a letter to Sir Joseph Banks, who was then President of the Royal Society of London. You will find it printed in the *Philosophical Transactions of the Royal Society* for that year. I give here the beginning of his letter and a translation, because it marked so important an epoch in the history of electricity and magnetism.

'XVII. On the Electricity excited by the mere Contact of conducting Substances of different kinds. In a Letter from Mr. Alexander Volta, F.R.S., Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir Joseph Banks, Bart., K.B., P.R.S.

'Read June 26, 1800.

'A Côme en Milanois, *ce 20me Mars, 1800.*

'Après un long silence, dont je ne chercherai pas à m'excuser, j'ai le plaisir de vous communiquer, Monsieur, et par votre moyen à la Société Royale, quelques resultats frappants auxquels je suis arrivé, en poursuivant mes expériences sur l'électricité excitée par le simple contact mutuel des métaux de différente espèce, et même par celui des autres conducteurs, aussi différents entr'eux, soit liquides, soit contenant quelque humeur, à laquelle ils doivent proprement leur pouvoir conducteur. . . .'

'Como, *March 20, 1800.*

'After a long silence, for which I will not try to excuse myself, I have the pleasure of communicating to you, Sir, and through you to the Royal Society, some striking results which I have obtained in following up my experiments on the electricity developed by the mere contact of metals of different kinds, and even by that of other conductors of differing kinds which are liquids or contain moisture to which they owe their conductivity. The most important of these results, which really embraces them all, is the construction of an apparatus which resembles the Leyden Jar in its effects, such as the shocks which it can give to the arms, etc., but which functions continuously, its charge being

renewed after each discharge; it possesses in fine an inexhaustible charge and perpetual action upon the electric fluid. It differs essentially from the Leyden

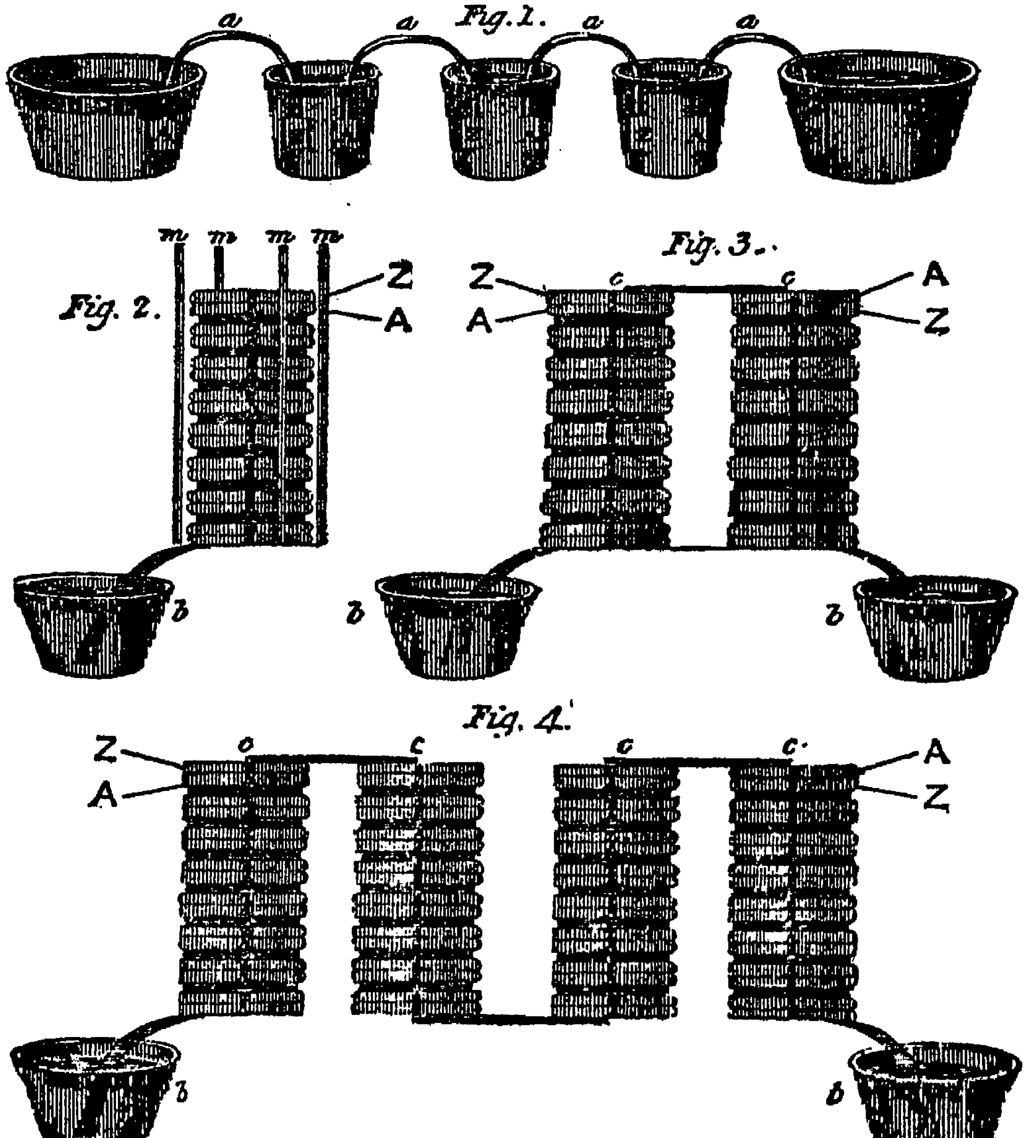


Fig. 24. Various forms of Volta's original 'Pile,' the forerunner of all electric batteries. (*Phil. Trans. Roy. Soc.*, 1800.)

Jar, both because of this peculiar continuous action and because, instead of being built like the ordinary jars or batteries out of thin insulating sheets of the substances generally reputed to be electric, together with conductors or so-called non-electrics, this new apparatus is

constructed solely from substances of the latter kind, which may even be selected from the best conductors and are consequently the most unlikely to be electric according to common belief. Indeed the apparatus I describe, which will no doubt astonish you, consists merely of a number of good conductors of different kinds arranged in a certain way. . . .'

Fig. 24 is taken from Volta's paper and shows various forms of his electric 'Pile.' He took a number of round discs of two metals, zinc and silver being found particularly effective. A number of somewhat smaller discs of paper, leather, or wood were also prepared, and these were soaked with water or a solution of salt in water. Volta found dirty water to be better than pure, and a salt solution better still, and pointed out that dirty water is more effective than clean water because it contains dissolved salts. The metals and moistened discs are stacked in the order shown in the figure, where A stands for silver (argent), Z for zinc, and the soaked sheets of paper or leather are drawn black. Volta discovered that the two ends of his pile behaved like the opposite plates of a charged condenser. He could get shocks by putting a hand in each of the cups connected to the ends of the pile. He says that the shocks are feeble compared to those given by a condenser (Leyden Jar) charged by an electrostatic machine, and likens them to the mild shocks given by the electric fish in a 'very languishing state,' but his pile has the remarkable property of *regenerating itself when discharged* again and again.

Volta had made for the first time what we now call a 'Battery.' Each pair of zinc and silver plates separated by the moistened disc is one cell in the battery. By

making a pile with as many as 60 pairs, it attained a voltage comparable with that of the high tension battery in a wireless set, and Volta found he could give himself shocks 'si cuisantes qu'elles devriendront insupportables,' especially if he had a cut in his finger. Of course there were no voltmeters or galvanometers in those days, and Volta estimated the effect of his pile by a rising scale of shocks, reckoning them the greater as the prickly feeling extended from the first joint of his finger to the second joint, to his wrist, or right up to his elbow. He found that if he put his hand in a vessel connected to the bottom of the pile, and touched successive cells with a moistened finger of the other hand, he could begin to feel a shock at the fourth or fifth cell from the bottom, and it regularly increased as he touched higher up the pile. Each cell adds to the total voltage. He made many experiments on the effects of the current upon the senses of taste, sight and hearing. He keeps coming back, in his paper, to the fact that the discharge from the pile seems endless.

'Cette circulation sans fin du fluide électrique, (ce *mouvement perpetuel,*) peut paroitre paradoxe, peut n'être pas explicable; mais elle n'en est pas moins vraie et réelle, et on la touche, pour ainsi dire, des mains.'

Actually the supply of current from a battery is not perpetual, for every battery runs down. In Volta's experiments he was drawing very minute currents from his cells, and they seemed to last for ever, or if they stopped working it was for the obvious reason that the soaked discs of paper or leather dried up. There is a little pile in the Clarendon Laboratory at Oxford

whose end plates are connected to two bells with an insulated clapper hanging between them (Fig. 25, Plate 5). The difference of potential between the bells is sufficient to make the clapper oscillate (see Fig. 9, Chapter I). The clapper is slowly discharging the pile, but the bell was set going in 1840 and is still

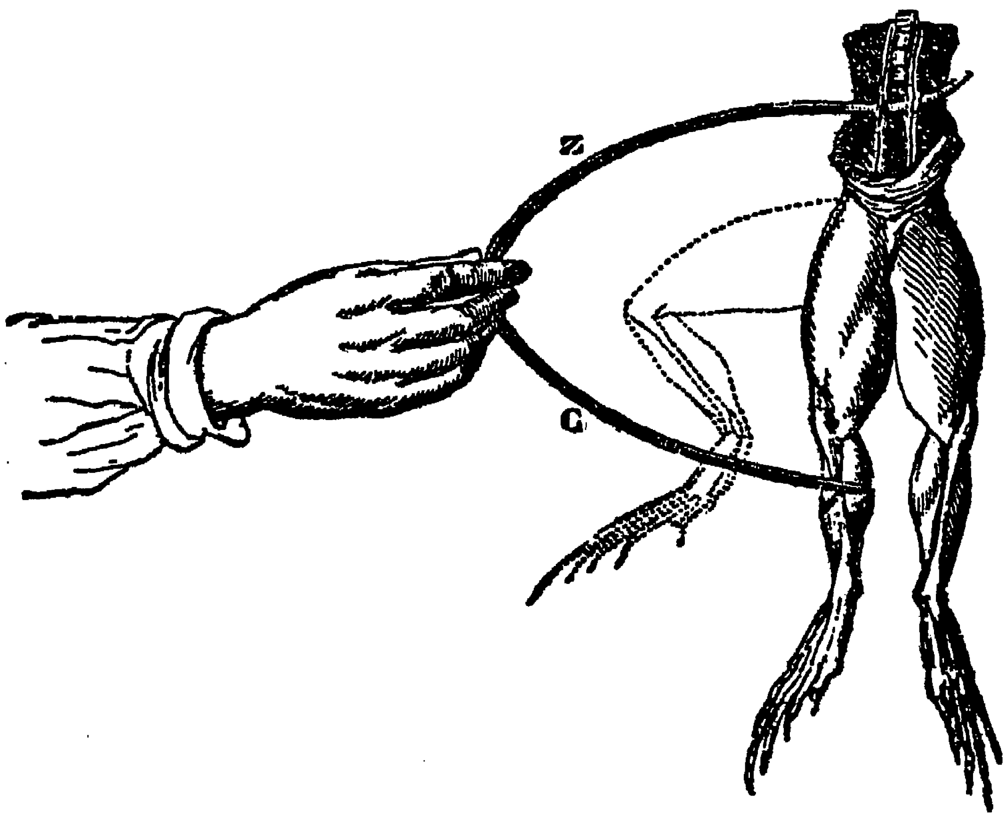
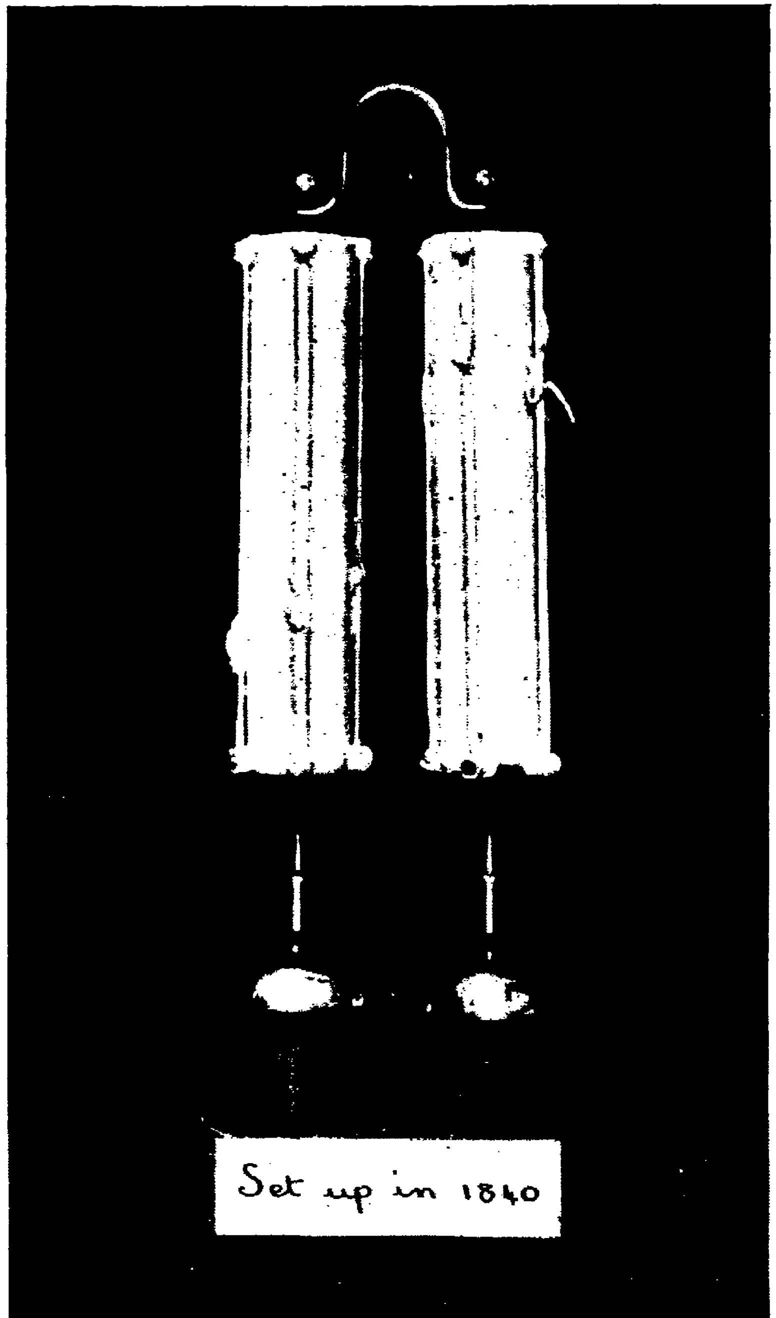


Fig. 26. Galvani's experiment with a frog's legs. The two pieces of metal Z (zinc) and C (copper) are held in contact in the hand. The one touches the nerves, and the other a leg. (*Ganot's Physics.*)

ringing! No wonder Volta thought he had found a perpetual supply of electrical current.

How did Volta hit upon the idea of the pile? The idea arose from an earlier experiment by Galvani, with whom Volta was having a tremendous scientific battle. Galvani's experiment is shown in Fig. 26. The legs of a frog which has recently been killed may be made to kick if they are given an electric shock. Galvani found by accident that if two different metals are held in contact, and one metal touches the nerves



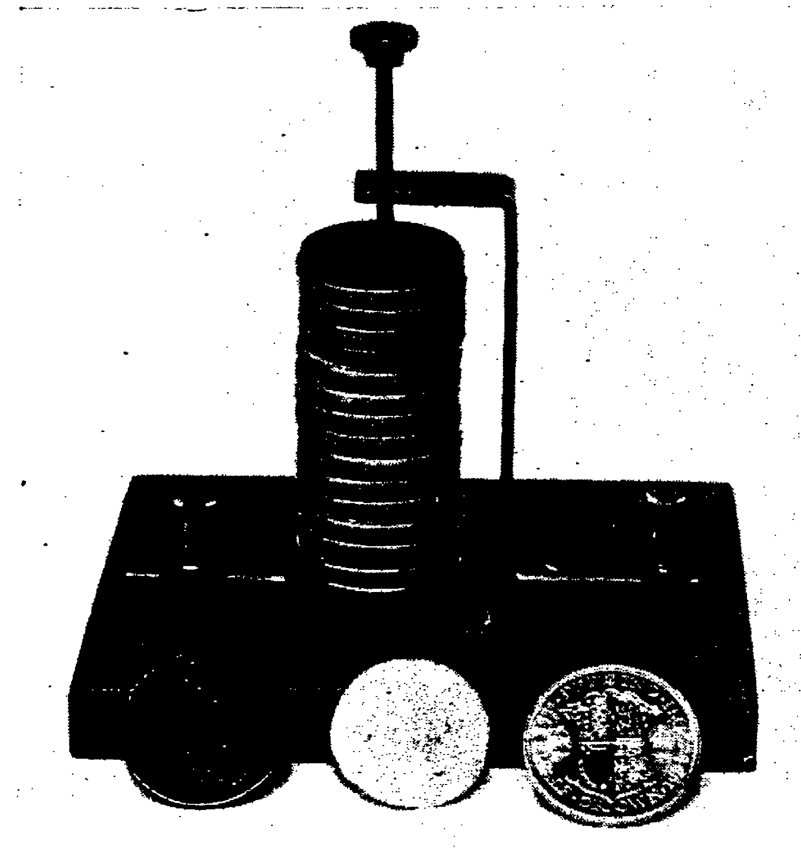


Fig. 27. Volta pile made from pennies and half-crowns

Fig. 25. (Left). A pile in the Clarendon Laboratory Oxford, which has been ringing a bell continuously since 1840

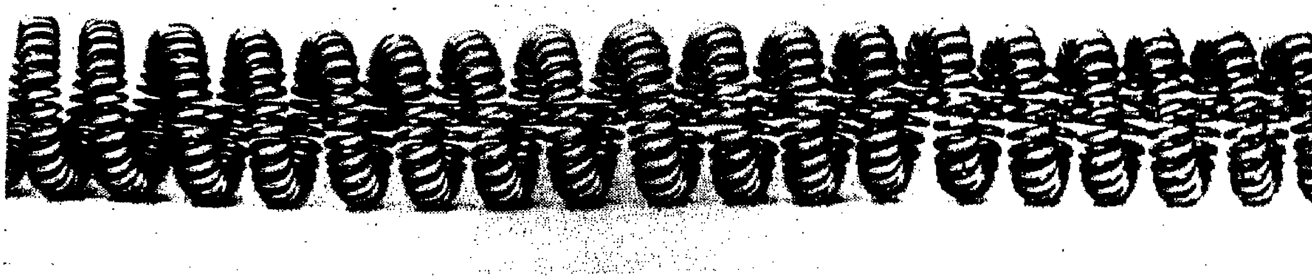


Fig. 29. Part of a coiled-coil filament for an electric lamp. The whole filamen has about 2,500 small primary coils and 150 larger secondary ones. (*Genera Electric Company*)

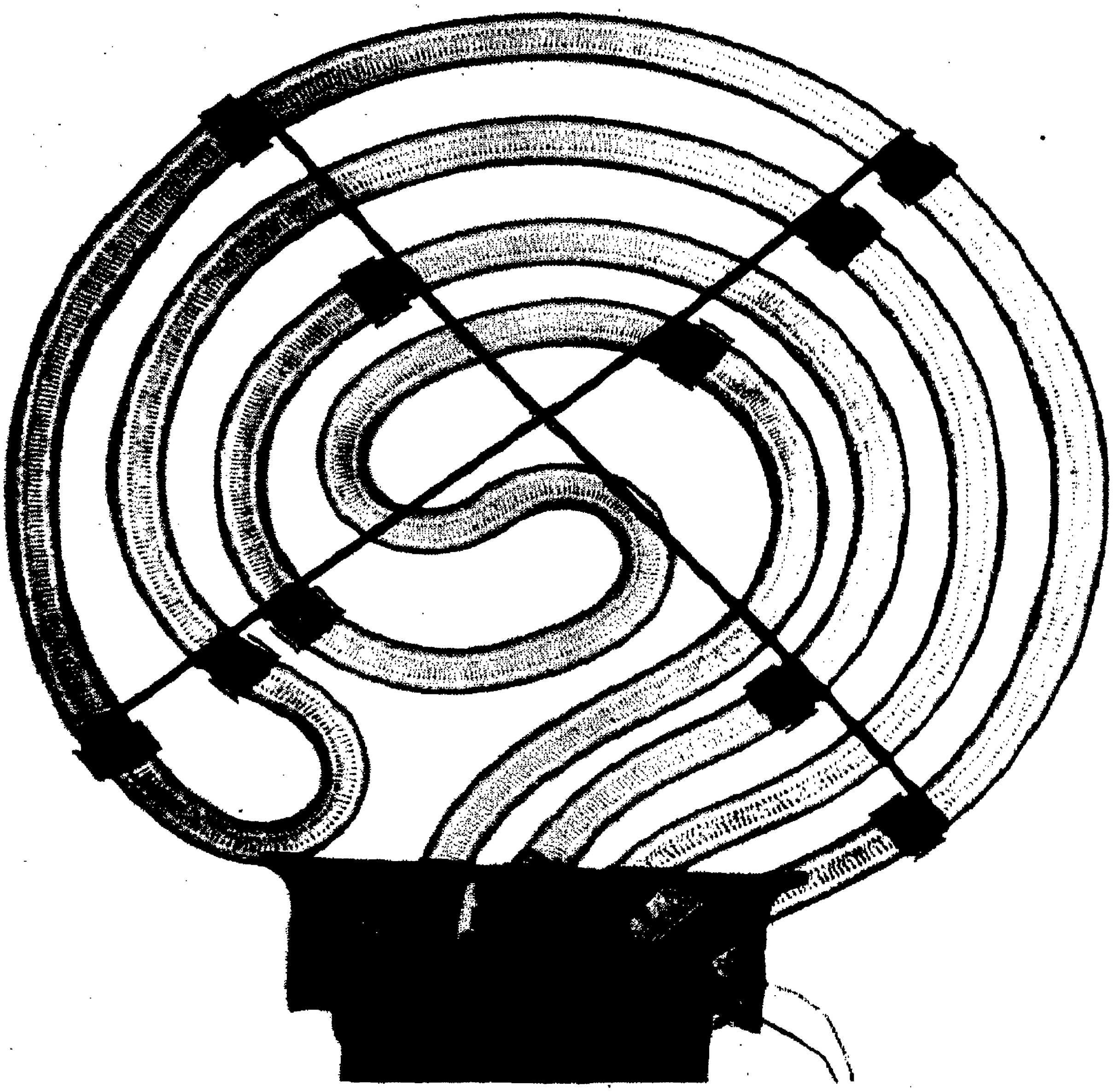


Fig. 30. An X-ray photograph of a heating element for an electric range. The fine coils of heating wire imbedded in insulating powder can be seen inside the iron tube which encloses them. (*Metropolitan-Vickers*)

of the legs while the other touches the legs themselves, the legs kick just as if a shock had been administered (see Fig. 26). Galvani believed that this was due to what he called 'animal electricity' for which the metals supplied a circuit but which came from the frog. Volta on the other hand believed the electricity to be generated by the contact of the dissimilar metals and was led to build his pile. Both contestants were partly right. As we would now put it, the dissimilar metals form a cell with the juices of the frog's body, and if they touch each other a current is driven round the circuit. The current is feeble, but sufficient to excite the nerves and make the muscles contract. The energy for driving the current comes from the slight chemical action between the metals and the muscles or nerves they touch. In Volta's Pile it comes from an action of the liquid upon the metals. Volta was sure it came from the contact of the metals themselves, and if you look at the illustrations of his pile (in Fig. 24) you will see that there is an extra silver plate at one end and zinc plate at the other which are really unnecessary and do not help to increase the strength of the pile.

It is easy to make up a pile out of handy materials. Copper and silver coins, along with some bits of blotting-paper soaked with a solution of common salt, will suffice. The coins should be stacked in the order, penny – blotting-paper – half-crown – penny – blotting-paper – half-crown, etc. In the Christmas lectures I made such a pile (Fig. 27, Plate 5), with the loose change in my pocket (having borrowed a few extra half-crowns), and we showed the different potentials of the two ends of the pile by means of a gold-leaf electroscope. The pile is much stronger if pieces of zinc

are substituted for the silver coins, since copper and silver give a very small potential difference. One can light up a pea lamp for a short time with some bits of copper and zinc and blotting-paper soaked in weak sulphuric acid.

Volta's discovery aroused tremendous interest and soon led to the construction of powerful batteries. The top illustration in Fig. 24 shows a forerunner of modern batteries which Volta called his 'crown of cups,' because the cups were often arranged in a ring. People soon started to make experiments with the strong continuous currents provided by such batteries, and discovered the effects which we will describe in later sections. This was the real beginning of the application of the electric current to the service of mankind The secret so jealously guarded by Nature had been discovered, and the consequences are incalculable. Yet the experiment which revealed the secret can be repeated by anyone with a few coins and some salt !

2. HEATING EFFECT OF ELECTRICAL CURRENT

When we say that an electrical current is running along a conductor such as a metal wire, what is actually happening ? The wire is solid all through and has no open channels along which anything can run. Yet the current only flows as long as there is a continuous metallic path. You are familiar with the way in which wires are used to conduct the current to lamps in our houses, to the telephone, or to the bells. If the metallic path is interrupted the current cannot flow. We cut the path when we 'switch off' the light, and we make it when we press a bell button. This suggests that something is actually flowing along the

wire, in the same way that water flows along a pipe. On the other hand, we cannot see anything moving, and the wire looks just the same after a current has run as it did before. It is not heavier or lighter, and it does not get worn out by the passage of the current.

However, something does actually happen to the wire: it gets *hot* when a current passes through it. If the wire is thick and the current is only small, this is not at all obvious. If on the other hand we pass a large current through a thin wire it gets very warm.

A good way of showing this effect is to stretch a wire between two rigid supports from one end of a long table to the other. The wire should be just taut, but not

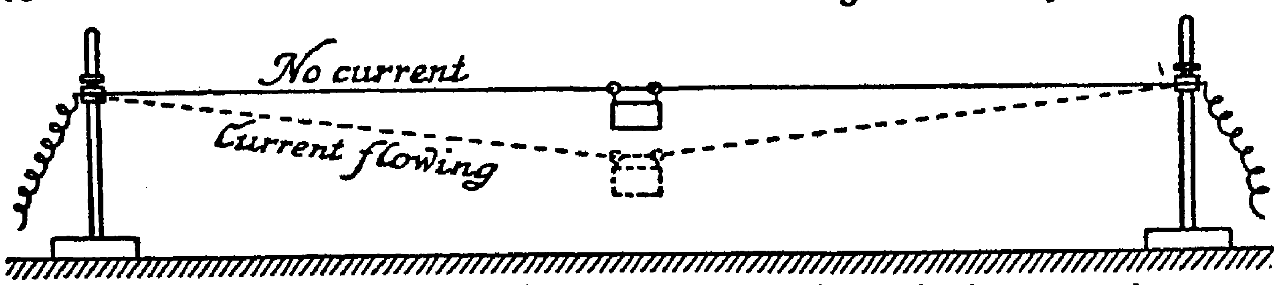


Fig. 28. The heating of a wire by a current, shown by its expansion.

under tension. A card is slung from it to make it easier to see any movement. When a current is passed through the wire, it sags down as shown by Fig. 28. If the current is cut off, the card rises again. The wire is heated by the current and its length increases when warm, allowing it to sag.

There is no need to do a special experiment to show this effect, for we make one every time we switch on an electric light. An electric lamp contains a very fine wire (the filament) which is heated white-hot by the current and gives out light. The art of making an electric lamp consists in producing the hottest possible filament. Only a fraction (one or two per cent) of the electrical energy put into a lamp is turned into

light, the greater part appearing as heat which is of no use to us in a lamp. The hotter we can make the wire, the larger is the proportion of light to heat. Tungsten wire is used because tungsten has a very high melting point (3655°C.) and lamps can be run at about 2700°C. The filament cannot be heated too much or it will become weak and break and the lamp will 'burn out.' All air must be removed from the lamp bulb or the tungsten will oxidize. Formerly it was customary to create as high a vacuum as possible inside the lamp, in order to ensure that no oxygen was present, but it was found that the tungsten vaporized rapidly in a high vacuum when it was hot, so that the filament soon became too thin and burnt out. This vaporization is slowed down by putting an inert gas (argon) in the lamps, and we now have 'gas-filled' lamps in which the gas pressure is about the same as that of the atmosphere when the lamp is alight. If the wire is coiled into a spiral instead of being straight, the coils keep each other warm, and so we can get a higher temperature for less current: we even have lamps now which have 'coiled-coil' filaments, a spiral of tiny turns being first made and this being itself coiled into a spiral. Fig. 29 (Plate 6) shows a greatly enlarged photograph of a portion of such a filament. The earliest types of lamp of the famous Ediswan variety had carbon filaments which could only be heated to a moderate temperature. They gave out a pleasant yellowish light but were inefficient compared with modern lamps, which give a bluish-white light from their intensely hot filaments and yield five times as much light for the same expenditure of energy. If you look at a lamp bulb, you will see its rating marked

on the glass, such as for instance, 230 volts, 40 watts. The watts are calculated by multiplying the 'voltage' by the current in 'amperes' running through the lamp. Modern lamps give rather more than one candle-power per watt. If only we could turn all the electrical energy they absorb into visible light we would get about fifty candle-power per watt.

The heating effect is also used in electric radiators. A common type has a wire coiled around a cylinder of heat-resisting material, the wire becoming red hot when the current is switched on. An electric fire really is a 'radiator'; it sends out radiant heat which warms us and other objects in the room without warming the air, so that we have the same pleasant effect as that given by a warm sun on a cool day. The so-called 'radiator' heated by water or steam works in just the opposite way by heating the air in the room in the first place, and the air in turn warms anything in the room. Since radiant heat is so important in an electric fire, a reflector is placed behind the heating element so as to throw all this radiation forward, and the efficiency of the fire depends very much on the shape and polish of the reflector.

The hot-plate of an electric cooking range, and an electric iron, have got coils of wire inside them which are heated by the current. The illustration in Fig. 30 (Plate 6) shows an X-ray photograph of one type of heating element for electric ranges. You are probably familiar with the X-ray photographs which show our bones. The rays from the X-ray tube pass right through our bodies, and cast a shadow of the bones, which are denser than the flesh, the shadow being registered on a photographic plate. In the present

case the patient is a heating element. It consists of an iron tube, inside which is a fine coil of wire, which can be clearly seen in the photograph. The coil itself is imbedded in an insulating powder so as to prevent its turns from touching the iron tube or each other and so making a 'short circuit.' When the current passes through the coiled wire, the iron tube becomes red hot and warms the cooking vessels resting upon it.

When a current runs in a wire, magnetic effects are produced in the neighbourhood which we will deal with in later chapters. For the present I wish to talk about what is happening in the wire itself, and the heating of the wire is important evidence that something is taking place inside it.

3. WHAT IS AN ELECTRICAL CURRENT?

What is this mysterious something which constitutes an electrical current and which can run along a metal wire without permanently altering it? In order to make observations upon it, we must somehow get it out into the open, for as long as it is inside the wire we cannot examine it. Sometimes on a country walk the rustling in the grass or undergrowth tells us that some small animal is running along, but we cannot see what it is until it is forced to cross an open space. In just the same way we must force the current to leave the conductor in order to have a good look at it.

It is possible in several ways to make an electrical current flow across an open gap. This happens, for instance, in the valves of a wireless set, where the batteries drive a current from plate to filament across a space which has been as highly evacuated as possible. When a spark passes in an electrical discharge,

the current has left a solid conductor and is flowing through the air. By studying the passage of the current under such conditions as these, its nature has been determined.

It is found that the electrical current is conveyed by a number of negatively charged particles called 'electrons.' The moving electrons jostle the atoms as they run along the wire, and increase their agitation so that the wire becomes hotter. The discovery of the electron by J. J. Thomson and the measurement of its charge and mass marked a great epoch and prepared the way for the rapid developments of atomic physics which have taken place in the present century. The atom had previously been considered to be the smallest unit of matter, and chemists had directed their efforts to identifying the different kinds of atoms and studying the compounds formed when atoms combine together. J. J. Thomson's experiments showed that electrons are much smaller bodies than atoms, and that in fact they are one type of unit from which all atoms are built. We shall have to refer to some features of atomic structure in these chapters, so I will give a very brief description of them here. At the centre of each atom, there is a positively charged *nucleus*, which contains nearly the whole mass of the atom. The positive nucleus is surrounded by a group of negative electrons. The nature of the atom, whether it is carbon or copper or gold, is determined by the nucleus, being in fact fixed by the magnitude of the positive charge associated with the nucleus, which remains constant whatever adventures in the way of chemical change befall the atom. On the other hand, the number of electrons surrounding the nucleus is

not constant. An atom can lose or gain one or more electrons, or can exchange electrons with another atom, just as a person might put on extra clothes or take some off, without losing his individuality. The normal or fully dressed state of an atom is that in which it has just so many negatively charged electrons as balance the positive charge on its nucleus, so that it is on the whole electrically neutral. If it loses electrons it becomes positively charged, and if it gains electrons it becomes negatively charged.

To sum up, there are two features of atomic structure which we must bear in mind. In the first place, the units of which the atoms are built are all charged. We cannot separate the electron from its negative charge, or the nucleus from its positive charge. You will now see why we must not say we are 'making electricity' when we produce an electrical charge or an electrical current. We do not make the charges, we merely cause them to move from one place to another. In the second place, you will understand why a wire is not altered after an electric current has passed along it. As the current flows the electrons drift along from atom to atom. Some leave the wire at one end, but equal numbers enter at the other. The atoms have exchanged one set of electrons for another, but, since all electrons are alike, the final state is like the initial state. Both conductors and insulators are built of electrons, but a conductor has the property of allowing the electrons to pass along it freely, whereas in an insulator the process is extremely slow.

One rather confusing point ought to be noted. We have agreed to say that a current flows 'from positive to negative,' this convention having been adopted

before anything was known about electrons. Now, the electrons which convey the current are *negatively* charged and of course flow from negative to positive. When a current is said to be flowing from the positive pole of a battery towards the negative pole, actually electrons are running in the opposite direction.

It is a most unlucky chance that the words 'positive' and 'negative' should have been chosen originally in such a way that our description of the flow of a current is just the opposite to the actual flow of electrons. Perhaps the following analogy will clear up the puzzle. A body which is 'positively charged' is one which has had electrons taken away from it, it is 'poor' in electrons. A body which is 'negatively charged' has more than its due share of electrons, it is 'rich' in electrons. Now suppose I take the spare cash in my pocket and hand it over to you. Ought I to say that a current of riches has passed from me to you, or that a current of poverty has passed from you to me? Unfortunately in the case of the electric current it was as if everyone agreed to say the current of poverty passed from you to me, before it was realized that the actual cash, represented by the electrons, went from pocket to pocket in the opposite direction. I hope you will see, however, that it does not matter which way we decide to say the current runs, as long as we are clear what is actually happening. We will always say that a current flows from positive to negative, remembering that the electrons are going the opposite way.

There is no space here to describe the experiments which determined the properties of the electron, but I may mention one effect which helps to illustrate

their nature. It is easily shown to an audience by projecting an electric arc upon a screen. Most large lanterns for showing slides are worked by an arc lamp. Two carbon rods are connected to the electric mains. They are brought together till their tips touch, and then separated by about one third of an inch. The current continues to pass after the rods are separated, and their tips become white hot. By adjusting the position of the arc in the lantern, it is possible to cause the lens to throw an image of it on the screen and we can see the luminous ends of the carbons with a flame between them. The positive rod is the hotter, and its end becomes hollowed out so that it looks like a volcanic crater; the negative rod becomes pointed (see Fig. 31*a*, Plate 7). The current is being carried by a stream of electrons which leave the negative rod and rush across the gap to the positive rod, hollowing its end into a crater by their bombardment. If now a magnet is brought up towards the arc, the white hot part will be seen to move towards one side (Fig. 31*b*, Plate 7), and if the magnet is sufficiently powerful the arc is 'blown out.' The electron stream is being bent to one side by the magnetic field.

I must also mention the way in which the charge on an electron is measured (Millikan's experiment), because it is so very ingenious. We have seen how an electrified soap bubble or other light object can be held up in the air or even driven upwards against the attraction of the earth by holding a charged body near it and so placing it in a vertical electric field. If the weight of the soap bubble were known, we could in fact measure the charge on it by seeing how strong an electric field is required to keep it suspended in the

air. Now the charge of a single electron is sufficiently large to keep a tiny drop of water or oil suspended in an electrical field in the same way. A mist of oil droplets is made by a kind of scent spray, and watched through a microscope. X-rays are passed through the air in which the droplets float; these rays chip electrons off some of the air atoms and from time to time an electron attaches itself to a droplet. The droplets lie between two plates which can be charged, and the electric field required to keep the charged drop suspended in the air is measured. The field is then switched off, and the mass of the drop is estimated by seeing how fast it falls, for the law connecting size and rate of fall is known. The charge on the electron follows at once.

We have called the electron a negatively charged particle, but we must not think of it as something like a small round ball which has been given a charge like that produced by an electrical machine. All that we know about the electron is that it behaves in a certain way, which is conveniently described by saying that it behaves as if it has a certain mass and negative charge. The mass and charge always go together, they are part of one and the same thing. We cannot picture the electron in terms of something we can handle or see. Imagine trying to describe houses to someone who had only seen cities from high up in an aeroplane so that the houses looked like little dots. You might tell him that the houses were built of bricks, but if he asked what a brick was it would not help him if you said that a brick was a very little house ! In the same way, we cannot draw a picture of an atom to show how it is built up. A picture suggests that its parts act upon

each other in the same way as the parts of a machine which we could see or handle, but this is just what they do not do. Mechanical parts are built of atoms, but atoms are not built of mechanical parts. Since it is always a help to make mental pictures, one can think of the heavy nucleus and the swarm of electrons held by its attraction as being like a sun with its planets, or someone's head with a cloud of midges round it. The pictures are equally good and equally bad; they are allowable as long as we do not interpret them literally.

4. THE SUPPLY OF ELECTRICAL CURRENT BY A BATTERY

Now that we have found an electrical current along a wire to consist of a stream of negatively charged particles, the electrons, which can move about easily in a metal, we can go back to consider the working of a voltaic cell or battery. As has been said above, Volta believed that his 'pile' was capable of regenerating its charge however often it was discharged. If we make electrostatic experiments with it, withdrawing a small charge for each experiment, this indeed appears to be the case. If a steady current is drawn from it, however, the battery finally 'runs down' and is used up like the high tension batteries in a wireless set. A battery can produce a total flow of electricity which is equivalent to an enormous charge as compared with the charges produced by friction, but it has its limit. This must of course be so, because we cannot expect to draw an inexhaustible supply of energy from the battery. The principle of the 'conservation of energy' was not appreciated in Volta's time.

A metal is like a reservoir of electrons. They can

flow from one place to another in the metal, and their number can be increased by giving the metal a negative charge or decreased by giving it a positive charge. Let us suppose we take an insulated sphere of metal such as zinc, about 1 centimetre in radius or four-fifths of an inch across. This sphere is connected to an electrical machine, such as a small Wimshurst, which charges it to 30,000 volts. The total electrical charge on the sphere is then 100 electrostatic units, this being the charge which rushes to earth when the sphere is discharged by a conductor or by the passage of a spark.

Let us suppose, on the other hand, that we were able to drain all the lightly bound electrons out of the sphere of metal, reckoning these electrons as two per atom. It is easy to calculate that roughly *260,000,000,000,000 units of electricity* would be obtainable, as compared with 100 units when it is charged by the electrostatic machine. As we shall see, this is precisely what happens as a cell is discharged. One metal plate in the cell is drained of all its free electrons, dissolving away in the process, and this enormous charge passing from one plate of the cell to the other keeps a current running for hours.

The model in Fig. 32 represents a zinc plate and a copper plate placed in a solution of zinc and copper salts. Each plate is represented by a series of packed discs, with black dots in the gaps between them. The discs represent positively charged atoms of either metal in our model, and the dots stand for the free electrons which can move about. Actually each metal atom consists of a positively charged nucleus and a large number of electrons, a neutral atom of copper having 29 electrons, and one of zinc 30. But in the case of

both metals, two of these electrons are held much less firmly than the remainder. These lightly bound

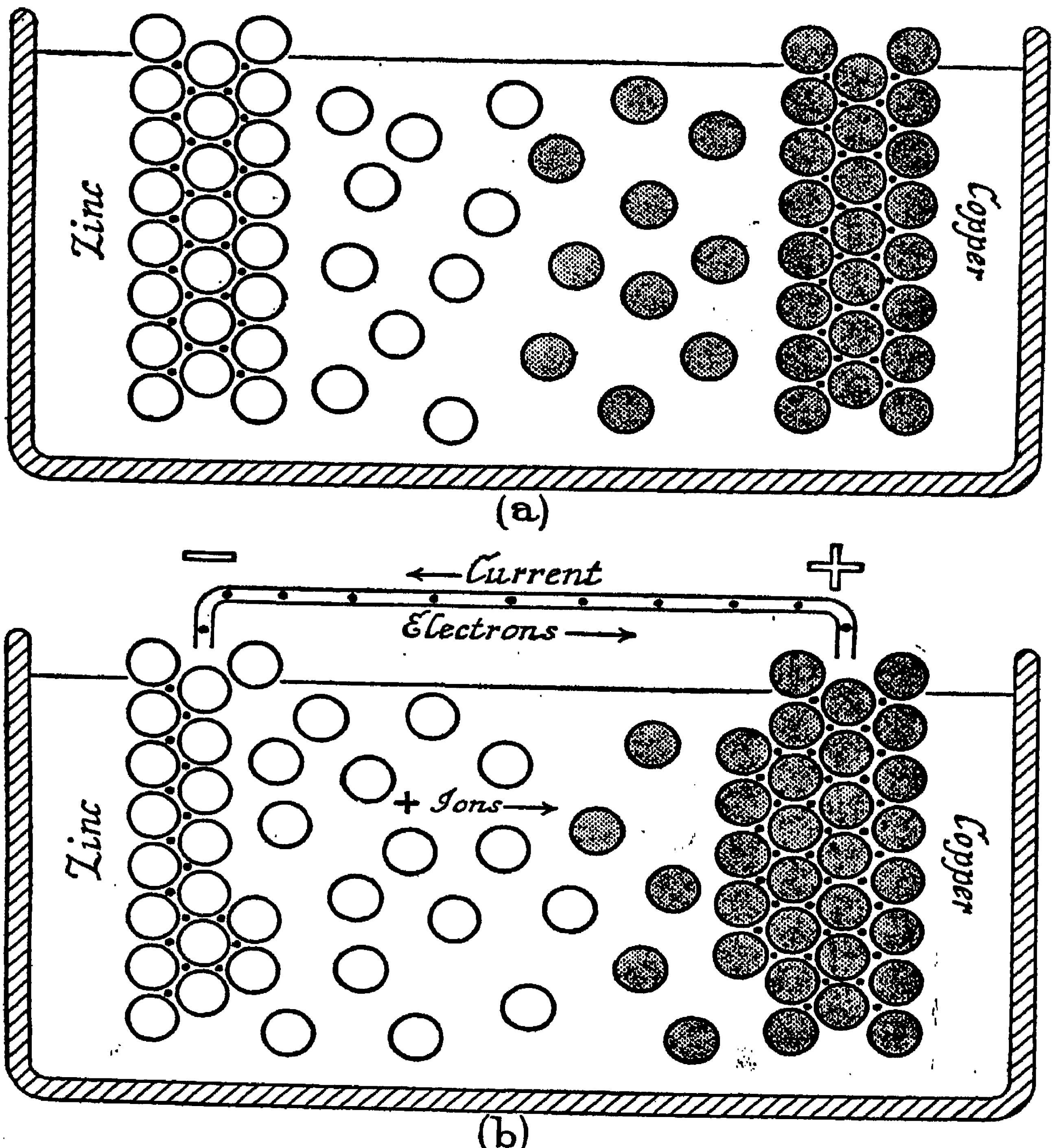


Fig. 32. A diagram to show the way in which an electric cell gives a current. The circles represent positively charged metal atoms (ions) and the dots represent electrons. In the lower figure electrons are able to flow from zinc to copper.

electrons become the conducting electrons when the atoms are packed together as a piece of solid metal,

and so we show them as separate black dots and suppose the remaining firmly attached electrons together with the nucleus to be represented by each disc. Since the disc is a metal atom minus two electrons, it has a positive charge twice as great as the negative charge of an electron.

The water in which the metals are placed contains dissolved salts of zinc and copper, for example zinc sulphate near the zinc plate, and copper sulphate near the copper plate. The zinc in a solution of zinc sulphate is in the form of positively charged atoms of zinc like those we have pictured as discs in the metal. These charged atoms, or 'ions,' to give them their scientific name, are drifting about in the water and are partnered by a corresponding number of negatively charged 'sulphate' ions which also drift about freely. The negative sulphate ions play no part in the changes we are considering except that of partners to the positive metal ions and so they have not been included in the picture.

Now it happens that electrons are much more firmly held by copper than by zinc. To put it in a graphic way, electrons would much rather be firmly imbedded in the copper structure than lightly held by the zinc structure, and if the electrons in the zinc could get a chance to pass over to the copper they would seize it. They cannot pass through the solution, which does not admit of their free passage like a metal. If, however, we join the zinc to the copper by a wire, it offers a free path for the electrons, as shown on the right-hand side of the picture. Electrons drain away from the zinc and run into the copper. As the electrons drain away from the zinc it falls to pieces and ceases to be zinc

metal. Its positive ions (the discs) float away into the solution because they no longer have any electrons to bind them to each other. On the other hand, the extra electrons in the copper attract copper ions from the solution and build up more copper metal as the picture shows. The process goes on until all the zinc has been eaten away and gone into solution.

This is what happens in a cell. If you look at the cells which work the bells in a house, you will see their zinc rods being gradually eaten away as current is drawn from the battery. When all the zinc is gone the battery is exhausted and new elements have to be put in it. The Leclanché battery used for working house bells has a conglomerate of carbon and other chemicals in place of the simple copper plate, and chemical changes take place which we cannot go into here, but the principle is the same.

As has been said before, we conventionally represent the direction of a current as being that in which positive charge flows, which is of course the opposite to that in which the negative electrons move. Since electrons go from zinc to copper, the current flows from copper to zinc, and we mark the copper as the + pole of a battery and the zinc as the — pole.

Suppose now that a dynamo, or more powerful battery outside the cell we are considering, drives the electrons from the copper to the zinc, against the direction in which they would flow if left to themselves. As electrons are drained out of the copper it dissolves, and correspondingly the zinc grows, so that we might end up where we started. The battery is then 're-charged' and ready to work all over again. This is the principle of the accumulator batteries which

can be re-charged when they have run down, though the kind of accumulator actually used has lead plates and we shall have to say a few words later about the changes which take place in it.

It is so important to grasp the idea of a cell, that I may perhaps be excused for repeating an analogy which I gave on the occasion of the Christmas lectures. I compared the zinc and copper plates in the cell to two dance parties going on in neighbouring houses. The discs represent the girls and the black dots the boys. Each metal represents a floor covered with dancers (we may overlook the feature that each fortunate girl has two partners in our model). The metal ions wandering about in solution are girls without partners, wallflowers in fact, who are sitting out. The sulphate ions merely represent the chairs they are sitting on round the wall, and take no active part in the proceedings. For some reason or other, the copper party is a much more desirable one to attend than the zinc party. We may either say that the partners are more pleasant or the refreshments more lavish, according to personal preferences. As long as there is no communication between the parties everything remains as it is. From time to time some ions in solution may join a metal plate, but a corresponding number must simultaneously leave the metal and go into solution, since the number of electron partners is limited. If, however, a means of communication is afforded by which the electrons can pass from one party to the other, the graceless young scamps will slip away by this back route to the more attractive party. The delighted copper wallflowers will find a new supply of partners and join the dance, increasing the

amount of copper metal, while disconsolate zinc ladies will have to swell the ranks of the wallflowers. We may extend the analogy to the re-charging of a battery, by comparing the external agency driving back the electrons to an energetic hostess forcing the electron gate-crashers to go back to their proper party.

You may say: If it is as simple as all this why not join a piece of zinc to a piece of copper by a wire, omitting the solutions in the cell, and get a current because the electrons will leave the zinc and pass to the copper? If we start with two uncharged pieces of metal, this actually happens for a brief instant, but it stops almost immediately. The passage of the electrons leaves the zinc with a positive charge and gives the copper a negative charge, and the charges accumulate until they discourage any further migration of electrons into the copper. On the other hand, if the metals are placed in a solution containing negative ions like the sulphate ions in our example, the transfer of electrons can go on till all the zinc is eaten away. Each sulphate ion can pair off either with a zinc atom or with a copper atom. To go back to our analogy of the party, when wallflower copper atoms join the dance because more electrons are available as partners, the empty chairs they leave can be used by the zinc atoms which have lost their partners. Charges do not therefore accumulate on the metal plates, and the electrons continue to flow from one metal to the other.

When the plates of a cell are connected by a wire two types of current are flowing. Electrons go from zinc to copper by the external wire making a *current*

from copper to zinc. At the same time there is a movement of positive ions inside the cell away from the zinc and towards the copper, so that a *current is flowing from zinc to copper* through the liquid in the cell. In other words, a uniform current is going round the whole circuit.

What has happened to our definition of potential? We have said that one conductor is at a higher potential than another if a current flows from the former to the latter when they are connected by a conductor. In the present case a current flows from copper to zinc outside the cell and zinc to copper inside. Is the zinc or the copper at the higher potential?

It is worth while discussing this paradox briefly because it has puzzled students. Many text-books tend to gloss over the difficulty by talking of 'contact potentials' between the surfaces of the plates and the solution and their 'maintenance by chemical action.' I believe that another way of looking at the problem appeals to many people and makes them see the solution of this apparent paradox.[1] The point is rather a tricky one, and I will not blame the reader who skips the next few paragraphs, though I hope he will come back to them again. We have defined potential differences as being measured by the work which has to be done when unit positive charge is taken from the body of lower potential to that of higher potential, just as height might be measured by the work required to pump water up a hill. The paradox arises because this is a definition made by someone sitting in a study armchair, and not working in a

[1] I wish to express my indebtedness to discussions with Mr. Gurney which suggested this way of stating the problem.

laboratory. In what form is the charge to be conveyed? In actual fact, it must either be a negative charge on electrons, or a positive charge on ions, because there is no such thing as a charge attached to nothing. The difficulty we have got into as regards a cell arises simply from our not realising that *we get different answers if we measure the potential by moving a charge attached to electrons or one attached to ions.*

The difficulty does not arise when measuring the difference of potential between two bodies which are alike, such as two pieces of copper. If no lines of force stretch between the two pieces of copper, they are at the same potential according to any method of measurement. Think of transferring the charge by electrons, for example. A certain amount of work has to be done to pull each electron out of one piece of copper, but this work is regained when the electron is handed over to the other piece, and as there is no electric field in the space between them the whole work done is zero.[1]

Now picture a piece of copper and a piece of zinc with no lines of force in the space between them. Since there is no electric field we might be tempted to say that they are at the 'same potential,' but the electrons tell a very different story. If we transfer an electron from copper to zinc, we have to do far more work to get it out of the copper than we regain when we put it in the zinc, since copper holds its electrons tighter than zinc. It therefore requires work to transfer a *negative* charge on electrons from the copper to the zinc, and if potential is measured by transferring electrons we would say that the copper has a higher

[1] To be strictly accurate, the transfer of the electron creates an electric field, but the work thus done is vanishingly small.

potential than the zinc. Now let the copper and zinc touch each other. Electrons will promptly leave the zinc to get more desirable situations in the copper, and will go on doing so until the copper gets a negative charge, just enough to discourage any more immigrants. In other words, when a piece of copper touches a piece of zinc at one point, lines of force stretch from the zinc to the copper everywhere else, actually representing a difference of potential of the order of a volt. This is called 'contact potential difference.'

On the other hand, inside the battery, charges can only go from one plate to another by the movement of ions in the solution. In order to transfer a positive charge from zinc to copper, a zinc ion must be detached from the metal and pass into the solution, and a copper ion must come out of solution and attach itself to the copper plate. The work required to exchange a metal ion between metal and solution is naturally different to that required to detach an electron. A battery is said to be on open circuit if the terminals are not connected and no current is flowing. In these circumstances the potentials of the plates adjust themselves so that no work would be done if a small positive charge were transferred by means of ions. In other words, the ions are able to insist that their definition of potential is the right one, and according to them the plates of a battery on open circuit are at the *same* potential.

Perhaps you can now see the result of this violent disagreement between the electrons and the ions as to what 'being at the same potential' means. Both cannot be right. If we also give the electrons a chance to assert their point of view by connecting the zinc to

the copper so that the plates can trade electrons, a fight begins. Electrons rush out of the zinc and into the copper. This upsets the balance inside the cell by making the copper more negative, and so some positive ions leave the zinc and a corresponding number attach themselves to the copper. The fight goes on until the combatants are exhausted, as we would say, the battery is 'used up' or 'discharged.'

We have seen that the electrons are trying to adjust the relative potentials of the plates to one value, and the ions in the solution are trying to adjust them to another. The difference between their points of view as to what 'being at the same potential' means, is the voltage or electromotive force of the cell; it is the pressure tending to drive a current around the circuit when the two terminals of the battery are connected. You will remember how surprised Volta was that a pile of *conductors* could have a difference of potential at its two ends, and it is indeed very astonishing at first sight, since it is a property of a conductor to equalize the potential all over its surface. The secret lies in the use of two types of conductor, metals through which only electrons can pass and solutions through which only ions can pass.

When making measurements of small electromotive forces or small currents with delicate electrical instruments, the student is often bothered by 'bad contacts.' When things go wrong, the trouble can generally be traced to his having neglected to screw up a terminal tightly or having made an ineffective and dirty soldered joint. Now we have seen that when two unlike metals touch each other, according to one way of defining potential difference, large 'contact potentials'

of the order of a volt are set up. How is it ever possible to make delicate measurements at all in an electrical apparatus, with these potential steps at so many points? The answer is that as long as the metals are in good contact everywhere so that there is universal free trade in electrons, the contact potentials just balance out. A current will not run round and round a circuit of different metals, driven merely by the contact potentials, because a potential step down in one place is just balanced by a step up in another place. Indeed, if we use electrons to convey the charge in defining potential difference, 'contact potentials' all vanish. If, however, there is some dirt between the metal surfaces in a carelessly tightened screw, or flux where a soldered joint has not 'run' properly, the electrons are no longer masters of the situation. The dirt contains *ions* which put a spoke in the wheel, and we have in fact a tiny battery which will play havoc with any delicate measurement, hence the importance of having good metallic contacts throughout.

The types of cell most often used are accumulators and dry cells. An accumulator battery is rather more complicated than the simple cell we have been considering. When charged, one plate is in the state of pure lead in a very spongy form with a skeleton of solid lead inside to give it strength. The other plate also has a lead skeleton, but this is coated with lead peroxide, PbO_2. The liquid is dilute sulphuric acid. As the cell discharges, both the metallic lead and the lead peroxide turn into insoluble lead sulphate which remains on the plates. Metallic lead gives up electrons in combining with sulphate ions and turning into lead sulphate (like the zinc in the previous case), whereas

the lead peroxide needs extra electrons to make the chemical change. Hence a current flows from the lead peroxide plate (positive) to the lead plate (negative). This goes on till the lead peroxide is exhausted; the battery can then be recharged by making the current run in the opposite direction. The electromotive force is just over 2 volts. One can tell the extent to which a battery is run down by measuring the specific gravity of the liquid in the cell. Sulphuric acid is heavier than water, and the acid is used up in making lead sulphate, so that the liquid gets lighter as the battery discharges. You will probably have noticed the instrument used for testing the density of the acid if you have watched a car battery being examined at a garage.

The dry cells used in torches or wireless high tension batteries have an outer container made of zinc, which is the negative plate, and a central carbon which is the positive. The carbon rod is surrounded by a paste of carbon and manganese dioxide, and the whole is moistened with a solution of ammonium chloride. The function of the paste is to mop up the electrons which run out of the zinc and into the carbon; it is a kind of 'electron blotting-paper.'[1] Such a cell is not reversible; we cannot coax the electrons out of the paste and back into the zinc by making the current run the opposite way, because they cause chemical changes which will not work backwards. When a high tension dry battery is discharged it is of no further use.

[1] Note that although the paste absorbs the electrons it does not acquire a negative charge because positive ions drawn from the solution also take part in the chemical change.

5. ELECTROLYTIC CONDUCTION

The voltaic cell provides examples of two ways in which a current may run. In the exterior circuit, there is a current of electrons along the conducting wire. Inside the cell, the current is represented by a transference of positively and negatively charged ions in the water, the positive ions going in one direction

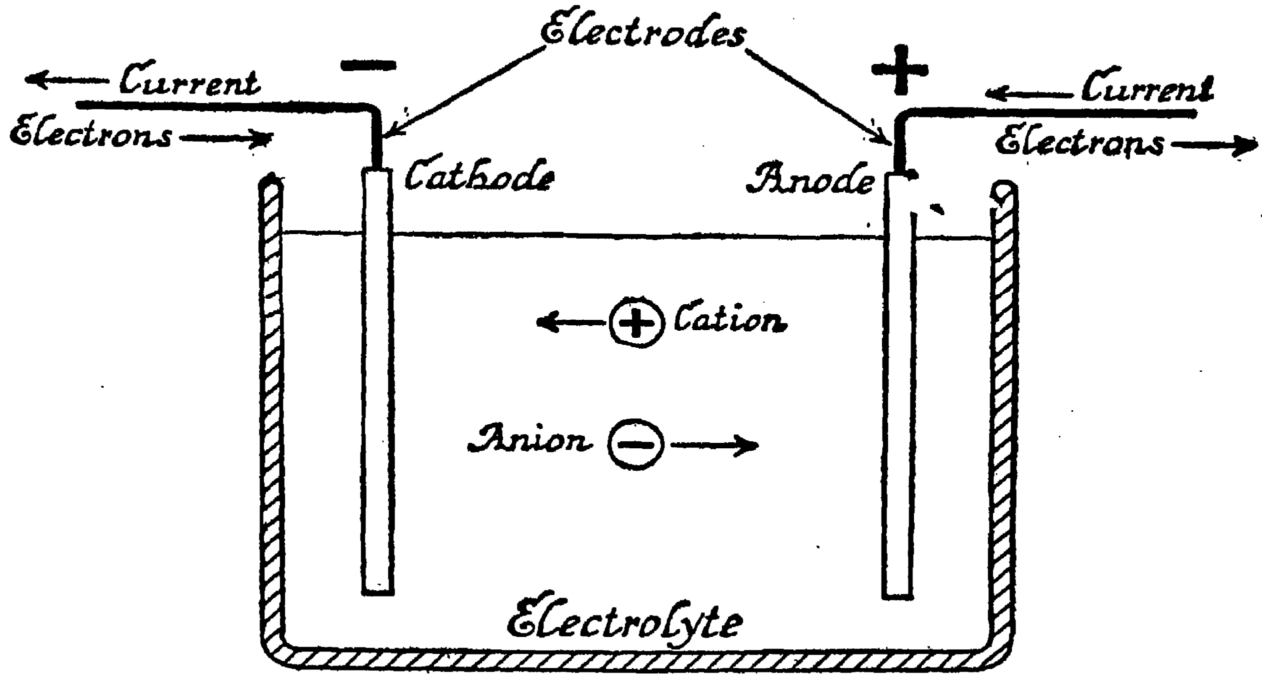


Fig. 33. A diagram to show the meaning of the terms used in describing electrolysis.

and the negative ions in the opposite direction. A solution which contains oppositely charged ions and so is able to conduct electricity is called an 'Electrolyte,' and the current is said to flow by electrolytic conduction. The commonest type of electrolyte is a solution of a salt, an acid, or an alkali, in water, but solutions of such substances in some other liquids than water are also electrolytes, and so are many salts when heated above melting point.

The great difference between the two forms of conduction, is that when a current is due to the movement

of electrons the conductor is in the same state after the passage of the current as before, whereas when the current passes through an electrolyte, ions or charged atoms move through the solution and collect at the points where the current enters and leaves the electrolyte. The positive ions move towards the conductor where the current is leaving the solution, the 'Cathode,' and the negative ions to the conductor where it enters, the 'Anode' (Fig. 33).

There is therefore a movement of matter, and the state of affairs is altered by the passage of the current. We are reminded of a well-known verse:

> Oh! I came to a river, an' I couldn't get across;
> Sing 'Polly-wolly-doodle,' all the day!
> An' I jumped upon a nigger, for I thought he was a hoss;
> Sing 'Polly-wolly-doodle,' all the day!

As long as the hero of Polly-wolly-doodle was travelling by road, he left no trace of his movement, but when he came to a river (the electrolyte) an ionic nigger had to move from one side of the river to the other before he could pass.

The driving of the ions across an electrolyte by the passage of a current has many useful applications. It is used, for instance, in plating one metal with another. Spoons and forks made of a cheap alloy such as German silver are covered with a thin coat of real silver which gives them an attractive appearance and keeps them clean and bright. The iron handle-bars and hubs of bicycles are plated with nickel which prevents the iron rusting. Recently chromium plating has come very much into favour for the radiators of motor-cars and

for bathroom fittings. In all these cases the coat of metal is deposited by electrolysis.

In silver plating the cathode is the object to be plated, for instance a spoon supported by two small pins so that the current can reach every part of it, and the anode is a rod of silver (Fig. 34). The electrolyte is a solution of a silver salt. When a current is said to

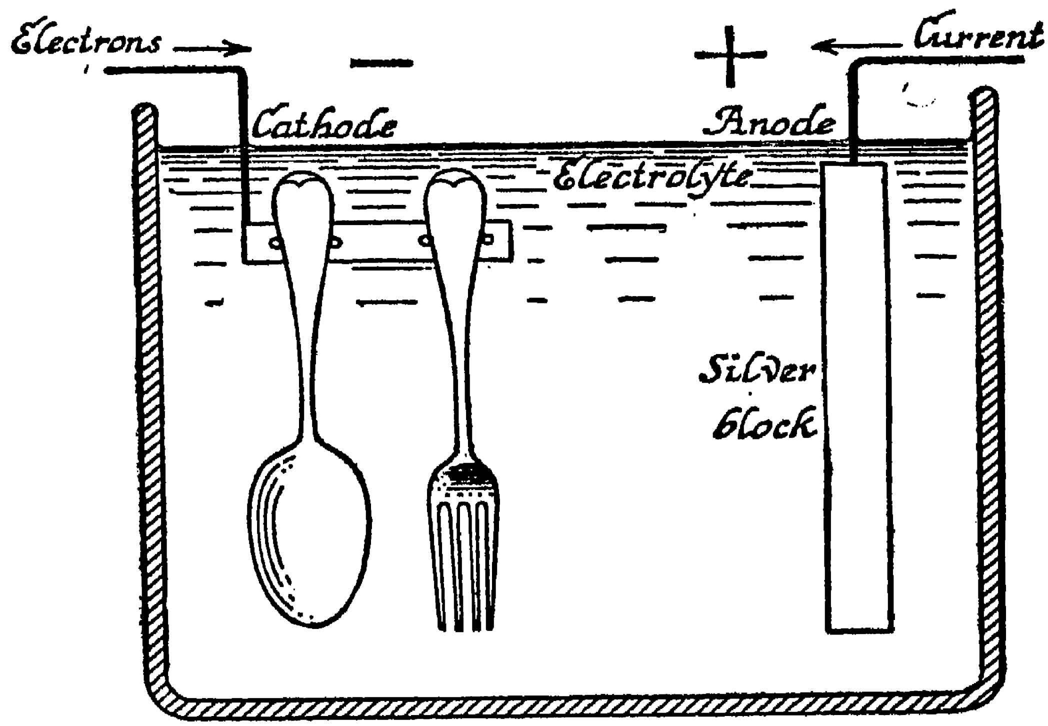


Fig. 34. Plating objects with silver.

be passing from the rod of silver to the spoon, we are actually pumping electrons into the metal of the spoon. Silver ions from the solution combine with these electrons to make metallic silver, which is deposited as a thin coat all over the spoon. At the anode electrons are being withdrawn, and so the silver rod is eaten away and silver ions pass into the solution to renew the supply which is being used up by the cathode. The current is effectively transferring metallic silver from the rod to the spoon.

In actual plating operations, hundreds of spoons and forks are hung from pins on a rack in the plating bath,

and the anode is a big block of silver. The rack is agitated up and down and the solution well stirred while plating goes on, so as to secure a uniform coat. Before the objects to be plated go into the plating bath, they pass through a series of other baths in which they are very carefully washed, in order that the silver coat may stick tightly to the surface. The composition of the plating solution is also an important factor in ensuring this result. It is desirable to have the plating on spoons and forks extra thick in certain places. When a spoon is lying in a drawer or on the table, it generally rests on the underneath surface of its bowl, and the plating at this point tends to wear through. One therefore sees, in a plating works, rows of spoons which have got their first uniform covering of silver travelling along a trough with just the bottom of their bowls touching the surface of the electrolyte, so as to get an extra coat at this point. The 'blanks,' or spoons and forks of cheap metal which are to be plated, are cut out of long strips of German silver and stamped into the right shape between dies.

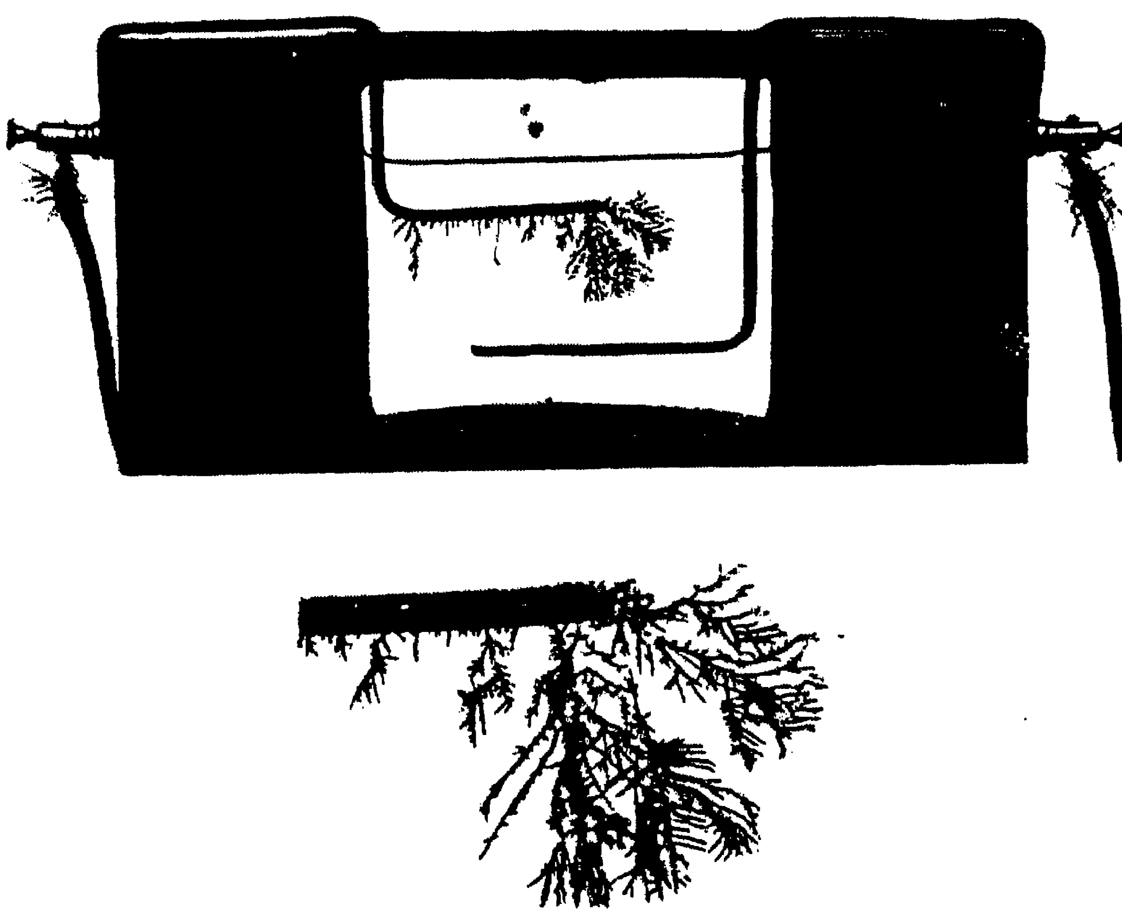
In another method of plating, the articles are placed in a metal basket. If they lay still, the places where they touch each other and the basket would get too thin a coat, but by keeping them moving an even coating is ensured.

Fig. 35 (Plate 8) shows how gramophone records are reproduced. The original record is made by a needle cutting into a rotating disc of soft wax. Sounds cause the needle to vibrate, and it draws a wavy track on the wax such as one sees on a record. When the record, or a copy of it, is put into a gramophone and the needle follows this track, the sounds are given out again. The

PLATE 7

(a) (b)

Fig. 31. (a) The electric arc. Note the crater in the upper carbon (positive). (b) The arc is deflected by a magnetic field



(a)

(b)

Fig. 36. A 'lead tree' growing in an electrolytic cell. An enlarged photograph of the tree is shown below

[p. 80

PLATE 8

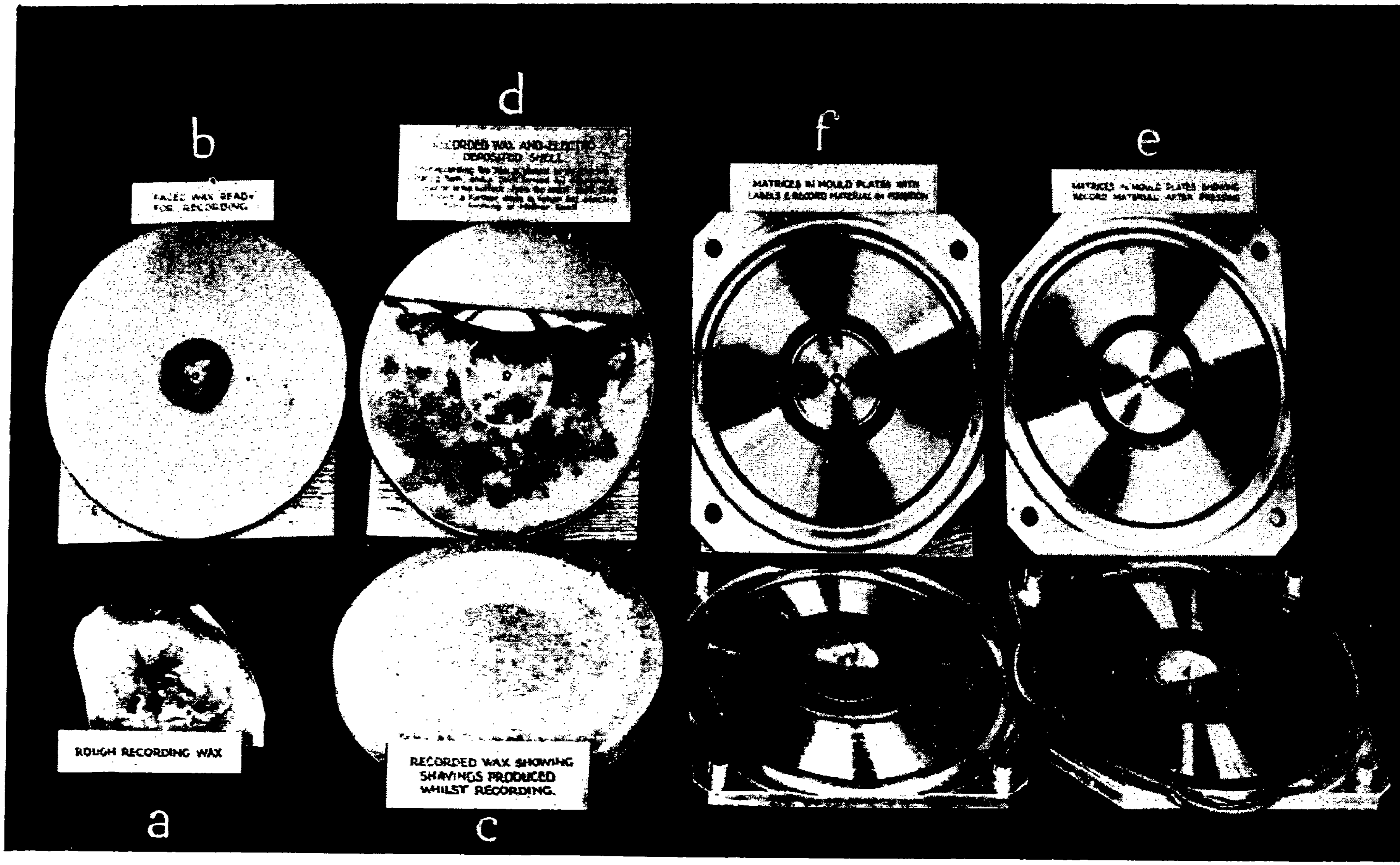


Fig. 35. Stages in making a gramophone record.

(*a*) The rough wax. (*b*) Surfaced wax ready to receive the track of the recording needle. (*c*) The wax plate after recording, showing the shavings made by the needle. (*d*) Peeling off the copper shell which has been deposited on the wax. (*f*) The copper shell is in the upper half of the mould, and the disc ready to receive the impress is in the lower

original record on the wax is covered with a thin layer of graphite, which is a conductor, and then put in a plating bath where copper is deposited on it. The sheet of copper can then be peeled off. It is a 'negative' of the original record, the track of the needle appearing as a ridge on its under surface. It can now be used as a die, for when pressed on round discs of a composition which is softened by warming, it prints the gramophone records with which we are familiar.

Another important use of electrolytic conduction is in the preparation of certain metals, particularly of aluminium. Although metals such as iron, copper, and tin have been used for thousands of years, it is only quite recently that we have started to make things of aluminium. At first sight this seems curious, because it is the commonest of all metals in the earth's crust, being for instance a constituent of granite and clay and many other widespread minerals. The proportions of the most abundant elements are roughly reckoned to be oxygen 50 per cent, silicon 26 per cent, aluminium 8 per cent, iron 4 per cent. There is enough aluminium in anyone's garden to make tons of the metal if it could be extracted. The difficulty has hitherto lain in preparing the aluminium from its minerals, for it has a very strong affinity for the oxygen with which it is combined. Other metals such as iron are also found in nature combined with oxygen, but it is possible to reduce the ore to metallic iron by causing the oxygen to combine with carbon, which has an even stronger affinity for it. Iron ore and carbon in the form of coke are heated in blast furnaces, where the carbon combines with the oxygen to form carbon monoxide which escapes as a gas, and

molten iron collects in the bottom of the furnace and can be run off. In other words, if we set the carbon and iron fighting for the oxygen it is the carbon which wins and the iron has to give it up. On the other hand, aluminium wins in the fight for oxygen against any other element which can be used cheaply, and this made people despair of ever getting cheap aluminium. Here is a quotation from Roscoe and Schorlemmer's *Chemistry* written in 1878.

'In the London Exhibition of 1862 a large number of various objects of aluminium were shown. The hopes which were then entertained concerning its general applicability have unfortunately not been fulfilled – the high price of the metal and of its alloys seems fatal to its general employment, and at present there is no prospect of the cost of manufacture being much reduced.'

Yet, now, aluminium is very cheap and is used in large quantities for many purposes. The overhead conductors of the 'Grid' are made of aluminium, for instance. The change has been effected by the use of the electric current. A compound of aluminium called cryolite is melted in an iron vessel lined with carbon, and aluminium oxide is added to the melt and dissolves in it. Carbon rods dip into this molten mixture and form the anode, while the vessel itself is the cathode. When an electric current is passed, molten aluminium collects in the bottom of the vessel. The oxygen is set free at the carbon rods, which burn away by combining with it. This is a case of a molten electrolyte. Five or six volts is sufficient to separate the aluminium and oxygen, and the heat developed by the current keeps the

mixture melted. Fresh aluminium oxide is added from time to time; the cryolite is not used up and only serves the purpose of making it possible to melt the mixture. Large amounts of electrical power are required in the manufacture, and works are therefore placed where this power is available. The British Aluminium Company has, for example, a big works at Kinlochleven in Scotland where water-power is used to generate the electric current.

The deposition of a metal at the cathode of an electrolytic cell can be shown in a striking way by growing a 'lead tree' (Fig. 36*a*, Plate 7). A narrow cell is made with flat glass sides, which can be placed in a lantern so as to be projected on the screen. It is filled with a solution of lead acetate, or some other soluble lead salt, and lead wires form anode and cathode. If a current is passed, lead crystals grow on the cathode, making a many-branched moss-like structure. If the current is reversed, this structure dissolves and the lead tree appears on the other wire. An enlarged photograph of the structure is shown in Fig. 36*b* (Plate 7). It is a very convincing proof of the crystalline nature of metals. It also shows how necessary it is to get conditions just right in a plating bath, where a strong uniform coat which sticks tightly to the object to be plated is required. The lead tree is so loosely attached that branches fall off it when they have grown beyond a certain size; it has just the characteristics which must be avoided in plating.

The changes which take place when a current passes through an electrolyte may be much more complicated than those we have considered so far. To take an example, let us go back to the dry cell which has been

described earlier in this chapter. At the zinc end of the cell everything is quite simple. Electrons leave the zinc when the cell is giving a current, and the zinc ions go into solution. At the other pole of the cell, electrons pour into a carbon rod. The carbon must get rid of these electrons somehow, and this is where the paste soaked with a solution of ammonium chloride comes in. The paste contains manganese dioxide (MnO_2), and the supply of electrons makes it possible for the manganese dioxide, together with the ammonium ions in the solution, to form manganese oxide (MnO), ammonia, and water. It is this action which makes the paste an 'electron blotting-paper' as we have called it above.

6. THE PASSAGE OF A CURRENT ACROSS AN OPEN SPACE

Under normal conditions, when a metallic circuit is interrupted by a gap, an electromotive force is unable to drive a current round the circuit. The electrons are bound to the metallic structure, and although they can move about freely inside the metal they cannot leave its surface.

There are two important ways in which we can break these bonds and allow the electrons to escape from the metal, when of course they will shoot across the intervening space and carry the current. Both ways really depend on the same thing, on giving the electron a knock which gets it over the sticky point of leaving the metal surface. You may think, if you like, of the electrons as a crowd of swimmers on the edge of a swimming pool on a cold day. They cannot make up their minds to take the plunge. Once someone pushes them in, off they go, swimming towards the other end. The electrons can be given a push either

by heating the metal to a high temperature, when they are jostled about by the increased agitation of the metal atoms, or by directing a beam of light upon the metal surface. Both effects have very important applications.

The liberation of electrons by heating a metal to a high temperature is known as the *thermionic effect.* The temperature of a body is a measure of the degree of agitation of its atoms or molecules. At high temperatures this agitation is very great; the atoms are being rattled so violently that bodies first melt and then break up completely to form a gas. If we heat water, for example, we increase the movement of the water molecules. From time to time a water molecule happens to get an extra violent movement, which enables it to escape altogether from the water surface and pass into the air, and the water is thus converted into water vapour. In just the same way, when a metal is heated, the free electrons share in the thermal agitation of the metal atoms, and here and there electrons acquire so hearty a movement that they escape altogether from the metal surface. We are in effect boiling the electrons out of the metal.

If therefore the metal on one side of a gap is made white hot, so that electrons can escape from it, a current will be able to bridge the gap. The most important application of this principle is in the construction of valves like those in a wireless apparatus. The valve of a pump or of a car engine is an arrangement which permits flow in one direction, but closes so as to prevent flow in the opposite direction. A thermionic 'valve' gets its name because it acts in the same way as regards the electric current. Electrons can escape from the hot

metal on one side and cross to the cold metal, but they cannot pass in the reverse direction. The valve is

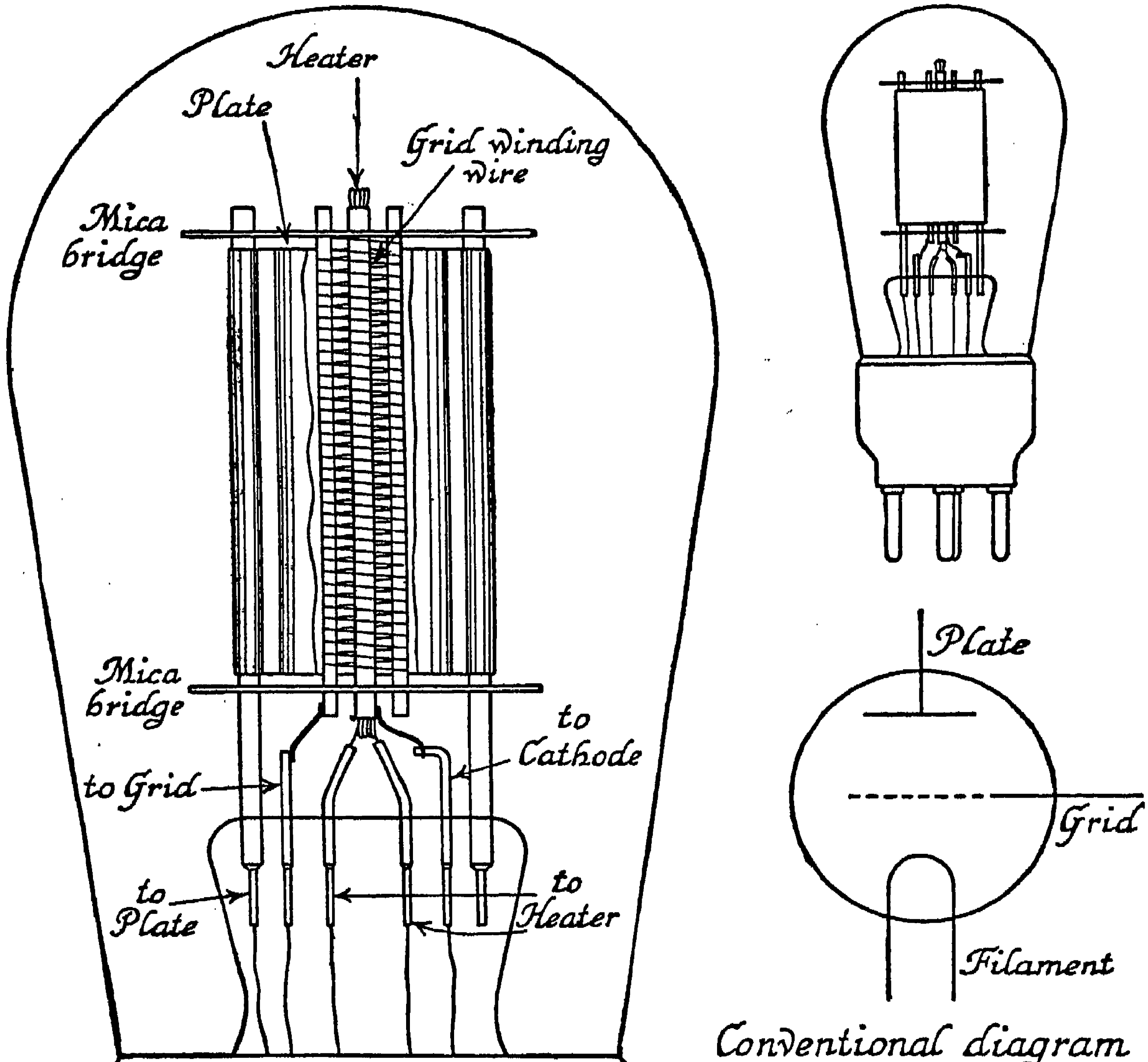


Fig. 37. A thermionic valve. Electrons are emitted from the *cathode*, which is heated by a fine wire inside it through which a current is passed. The cathode is surrounded by a *grid* formed of wire wound round two insulating supports. The *plate* is a flattened cylinder, which has been partly cut away in the figure so as to show the cathode and grid. Connections to the rest of the apparatus are made by the pins at the bottom of the valve. The lower figure on the right-hand side shows the conventional way of representing a valve in diagrams. (*Ferranti.*)

therefore an arrangement which allows current to pass in one direction only.

A valve which has a hot electrode and a cold one,

and serves merely to confine the current to one direction, is called a rectifying valve. A simple modification, however, gives such a valve extremely useful properties. What is called the 'three electrode valve,' and more complex types of valves which are based on the same principle, have increased the possibilities of electrical apparatus more than any other device ever invented.

One type of valve is shown in Fig. 37. The electrodes are placed in a glass bulb which has been highly exhausted.[1] The *filament* is a fine wire (tungsten or nickel) which is heated by a current at low voltage so that electrons are able to escape from its surface. It is found that electrons escape more easily when the wire is coated with thorium oxide, or a mixture of barium and strontium oxides. Such coated filaments need not therefore be heated to so high a temperature, and are more economical as regards current. The illustration actually shows a tube in which the cathode—from which the electrons escape—is heated by a separate coil placed inside it, and in other types of valve it is heated inductively by alternating current (see Chapter IV) but the principle is the same. The *plate* is the electrode to which the electrons liberated from the filament flow. This current is driven by a much higher potential (one or two hundred volts), the plate being of course positive with respect to the filament so that it attracts the electrons.

In addition there is a third electrode, generally surrounding the filament, which is called the *grid*. It has many forms, such as a wire spiral, a gauze, a plate

[1] When the tube is being evacuated, it is a common practice to get rid of the last traces of gas by evaporating or 'flashing' a fragment of metal, generally magnesium, inside the tube. This produces the familiar metallic coating on the inside of the glass.

pierced with holes, or just a plain conductor in the neighbourhood of the filament, but its purpose in each case is to exert an electrostatic influence on the electrons coming from the filament. You must picture a cloud of these liberated electrons surrounding the hot filament; if they come under the influence of the positive plate they rush to it and carry the current through the valve. The grid determines the number which are allowed to start on this journey. If a strongly negative grid surrounds the filament, the electrons are all discouraged at the outset, being repelled back to the filament. As the grid is made less negative, perhaps even slightly positive with respect to the filament,[1] the electrons are permitted and even encouraged to leave and the current through the valve increases. We may compare the grid to the gate which controls the flow of water from a reservoir into a pipeline running down hill to a hydro-electric power station. The water acquires tremendous energy in running down hill, just as the driving of current through the valve by the high tension battery represents a large expenditure of energy. It requires hardly any energy, however, to open and close the gate at the top which allows the water to start on its journey. In the same way small alterations of potential of the grid, such as those produced by linking it to an aerial which is receiving wireless waves, can be made to control powerful currents.

The valve is therefore an ideal instrument for turning a weak variation of current or potential into a powerful one. It has no moving parts to go wrong or

[1] i.e., as its potential is raised until it is slightly above that of the filament.

wear out. If we want to magnify an effect very greatly, we put a number of valves in series, making the plate current from one affect the grid potential of the next, and so on along the chain. This piece of apparatus has given us an almost incredible power of magnifying a weak effect into a strong one, and so of arranging that

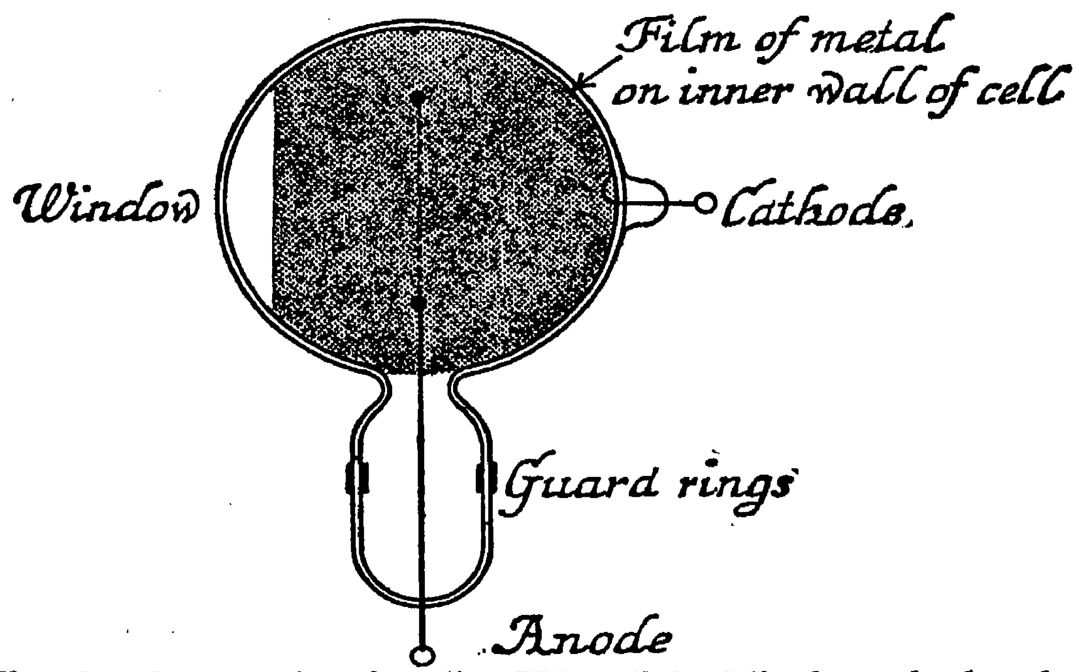


Fig. 38. A photoelectric cell. When light falls through the clear part of the glass marked 'window' upon the inner coating of caesium, electrons are liberated and driven across to the central grid marked 'anode.'

an event in one part of the world should have an immediate effect in another. As an instance, when the new wing of the Museum of Science and Industry was opened on February 11th, 1936, in New York, all the lights of the building were turned on by the lighting of a candle in Faraday's laboratory at the Royal Institution in London. The candle caused a current in a photoelectric cell, which by valve amplification and wireless transmission closed the switch in New York. Such an example gives us an idea of the new possibilities introduced by the valve, which is one of the stupendous inventions of our era.

The liberation of electrons from the surface of a metal by light is called the *photoelectric effect.* A photoelectric cell is shown in Fig. 38. The metal surface from which the electrons are set free is a thin film of the metal caesium, and the electrons flow to the positive electrode marked anode in the figure. In the dark, the electrons are unable to escape from the caesium, and no current can pass through the valve. If light is allowed to fall on the caesium, electrons are liberated, and a current flows which is proportional to the intensity of the light. Caesium is used because of a characteristic feature of the photoelectric effect. White light is composed of light of different wave-lengths, the red end of the spectrum representing the long waves and the blue end the short waves. If the spectrum is split up into its different colours, and these are allowed to fall separately on the photoelectric cell, it is found that no electrons are emitted unless the wave-length is less than a certain limiting value. Red light cannot do it, but in the yellow region we reach the limiting value, and any kind of light which is further towards the blue end of the spectrum is effective. In the case of most metals we actually have to go beyond the blue end of the spectrum, into the invisible region called the ultra-violet, before we get any effect. The alkali metals sodium, potassium, rubidium and caesium, however, are affected by light waves in the visible spectrum. Caesium is the best of them all, because nearly all the different colours in white light are able to liberate electrons from this metal.

A study of the photoelectric effect has shown that the light hands over its energy to the electrons by giving one here and there a tremendous blow, while

leaving its neighbours undisturbed. The shorter the wave-length of the light, the greater is the amount of energy received by each electron. If the energy is sufficient, an electron can escape from the metal. Most metals hold their electrons so firmly that ultra-violet light is necessary to shake them loose, but caesium parts with them comparatively easily and hence is sensitive to light in the greater part of the visible spectrum. As to the way in which the light gives the electrons these parcels of energy, physicists have agreed to accept it as one of the fundamental facts of Nature and do not try to 'explain' it. It is the fundamental way in which energy in the form of radiation such as radiant heat, light, or X-rays, is handed over to matter.

The photoelectric cell is important, because it is possible by means of such a cell to turn a *light signal* into an *electric signal.* Here are some ways in which it can be used.

Talking cinematograph pictures. When the pictures are recorded in the studio, a photographic record of the sound-waves is simultaneously made on the film. The sound vibrations open and shut a narrow slit, through which light falls on the film as it moves, so that, when the film is developed, the 'sound-track' is covered by dark and light lines as in Fig. 39 (Plate 9). When the film is being displayed, light passes through the sound-track and into a photoelectric cell. As the dark and light patches pass in front of the light, the current in the cell becomes small or large respectively. The current in fact varies in the same way as the pressure in the original sound-waves, and, by amplifying the current by valves and passing it into a loud speaker, we get a repetition of the sounds.

Television. A spot of light is made to move backwards and forwards, up and down, all over the object to be televised. When it falls on a bright part of the object, a lot of light is reflected into a photoelectric cell placed near by, and a strong current passes. When the spotlight falls on a dark part, very little current passes. The currents from the photoelectric cell are amplified by valves, sent to the receiving station, and there made to alter the brightness of another spotlight which is moving over a screen in just the same way that the original one moved over the object. Hence bright and dark parts of the object appear bright and dark on the screen and we see the original object. The 'scanning,' as it is called, is so rapid that the whole screen appears lit up at once.

Opening doors, counting objects, detecting smoke, etc. These various applications depend on using a cell to pass a current when a light is on and stop it when the light is off. The use of a cell to open doors is shown in Fig. 40. A lamp mounted on one side of the approach to the door sends its rays into a photoelectric cell on the other side. As long as the cell receives the light, a current passes through it, and this current holds a switch in the 'off' position, i.e. prevents the powerful current flowing which works the door-opening machinery. Directly anyone walks past, like the waitress in the photograph with the tray, who obviously would find it awkward to open the door herself, the light is cut off for a moment. The current in the cell stops, and the switch moves to the 'on' position so as to start up an electric motor which politely opens the door. It is arranged that the motor is switched off again when the door is wide open, and the door is slowly closed by a

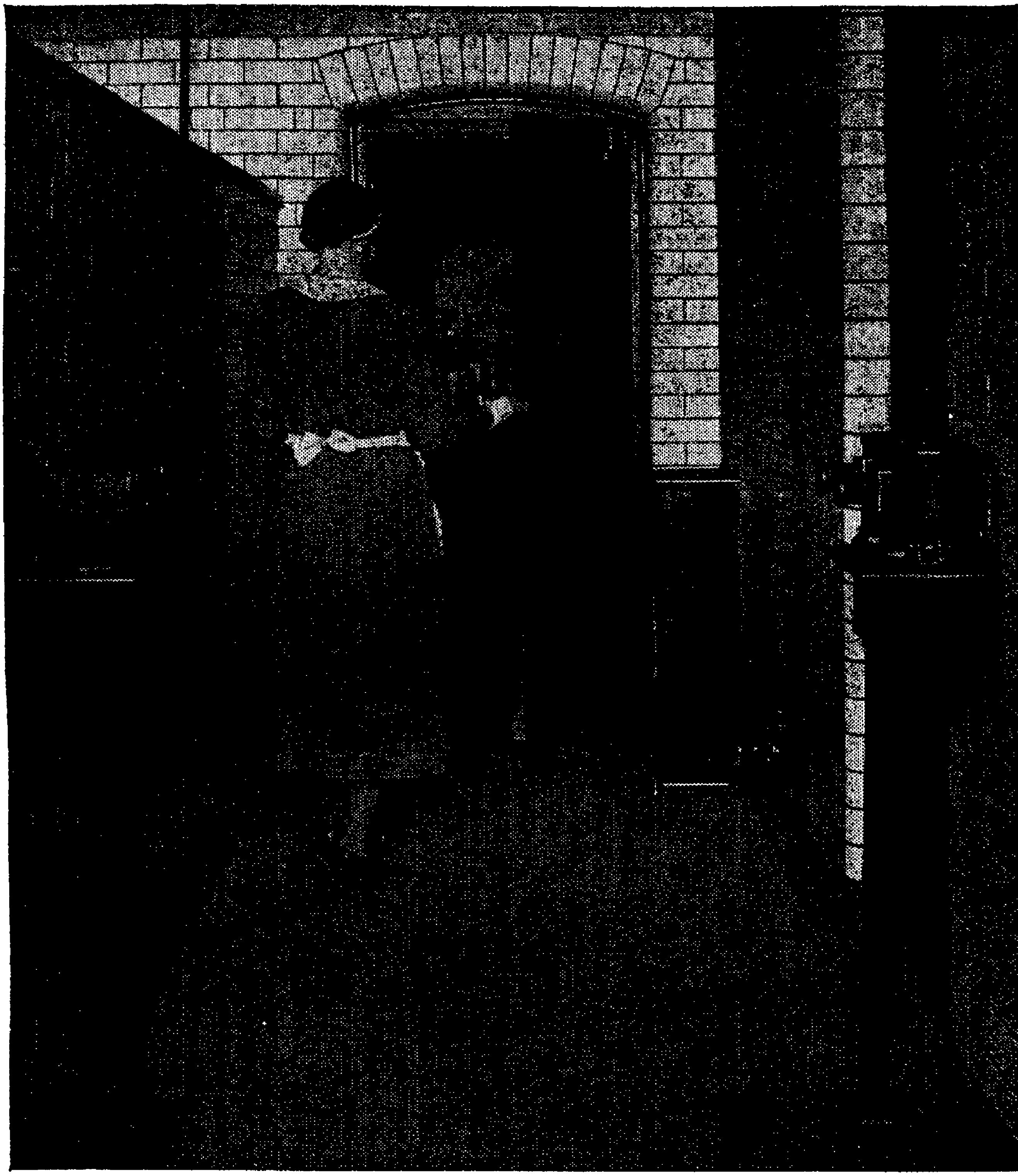


Fig. 40. Opening a door by photoelectric cells. Two projector lanterns are mounted on the left hand side in the foreground, and two photoelectric cell equipments on the right hand side receive their beams. When anyone approaches the door, the cutting-off of the light works the door-opening mechanism in the box seen on the right hand side of the door. *Two* cells are used, for it is then possible to arrange that the door should only open when the ray of light farthest from it is the first to be cut off, i.e., when someone is approaching the door. When the ray of light nearest the door is the first to be cut off by someone who has already been through it, the door remains shut. (*Witton-Kramer.*)

spring giving one plenty of time to walk through first. Smoke-detectors work in a similar way. A light shining across a room near the ceiling falls on a cell, and as long as the cell receives the light a switch is held in the off position. If a fire causes the room to fill with smoke, the light is cut off, the switch closes, and an alarm bell is rung. In counting such things as loaves of bread, they pass along a belt conveyor and each loaf cuts off the light as it goes past. The current works a counter like a cyclometer. So many gadgets can be made to work with photoelectric cells that they provide a gloriously happy hunting ground for inventors.

Finally, I wish to say something about the way in which a current leaps across an open space even when not encouraged to do so by heat or light. We have seen in the first chapter that a spark will pass through the air between two conductors if the difference of potential is sufficiently high. The discharge occurs without external help when the strength of the electric field is greater than 30,000 volts per centimetre. This is in reality a very complicated effect which is still only partly understood, but we can give a general picture of how it happens. There are always a few charged molecules, or ions, in the air. When the electric field is very strong, the positive ions rush one way, and the negative ions the other way, through the air. They jostle the other neutral molecules so violently that they knock electrons off them, just as rude passengers rushing to catch a train might knock away the handbags of more sedate travellers. These molecules which have lost their electrons become ions in turn, join the mad rush, and create still more ions. In the end so many

ions are produced that a conducting path is formed and a spark passes.

If the pressure of the air is diminished, it at first becomes easier to pass a spark. The jostling ions can rush more quickly through the crowd, and their collisions with the others are correspondingly more violent, so that they produce many more ions. If we go on diminishing the pressure by pumping away the air inside a vessel, it becomes much harder again to pass a spark. The platform is so empty that the rude passengers have plenty of room and do not crash into anyone!

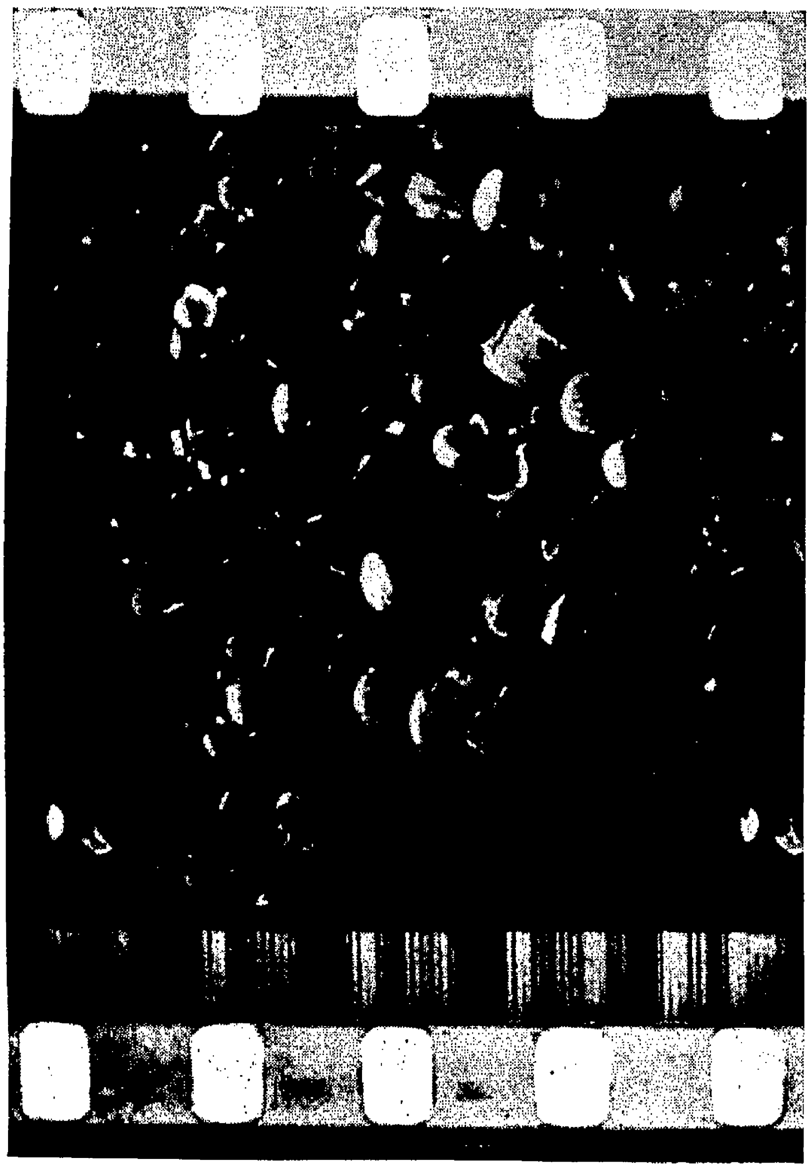
To sum up, let us collect our ideas about the way in which this mysterious thing we call an electric current can flow. All material bodies consist of charged particles, the nuclei of the atoms being positively charged and the electrons which surround them being negatively charged. In some bodies, which we call conductors, the electrons can be handed on from one atom to another. If a potential is applied, the electrons drift along the conductors. In nearly all the cases we shall be dealing with, the electric current is of this kind. The electrons flow around a closed *circuit*, not accumulating at any one point but moving steadily along.

Electrolytic conduction is a special case. If we take a lump of matter and move it from one place to another, we do not create an electrical current, although the matter is built of electrified particles and we are setting them in motion. There is no current because equal positive and negative charges are moving together. We can arrange, however, that when the matter goes from one place to another, some of the

electrons shall go by one path and the atoms minus these electrons by another. If you think it out, you will see that this is what is happening in a battery or in a plating bath. The current conveyed by the moving charged atoms inside the solution is balanced by a current of moving electrons in the outside circuit. In this case the electrons are not going round and round the circuit. They are starting from one reservoir and draining into another, though of course matter must move at the same time so as to provide a new home for them.

Finally, we have seen how it is possible to make electrons cross an open space where no matter is present. A current flowing across a gap in this way lends itself to very perfect and delicate control by a valve, and this power of control has opened up a new world of possibilities which will be described in the last chapter of this book.

PLATE 9



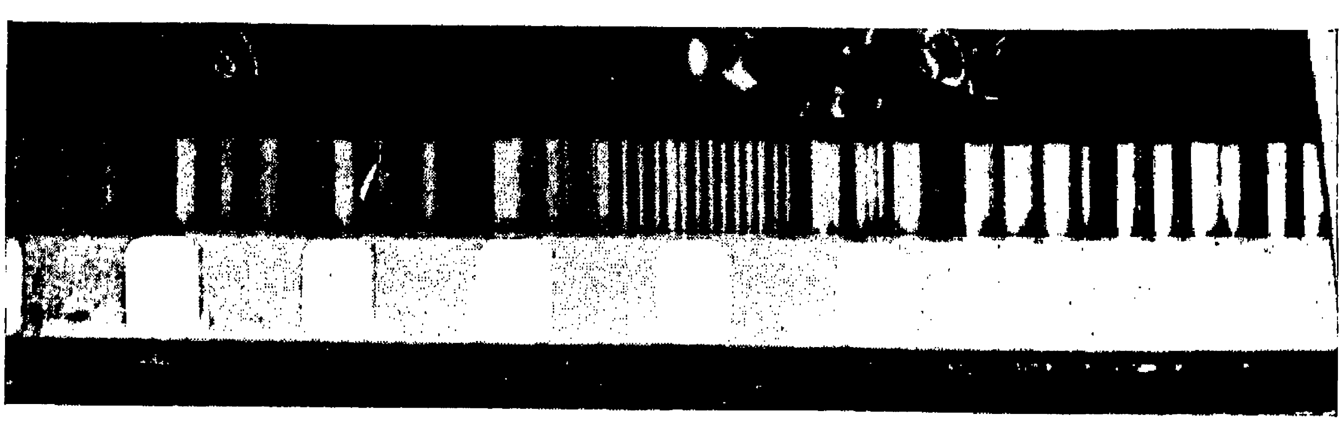
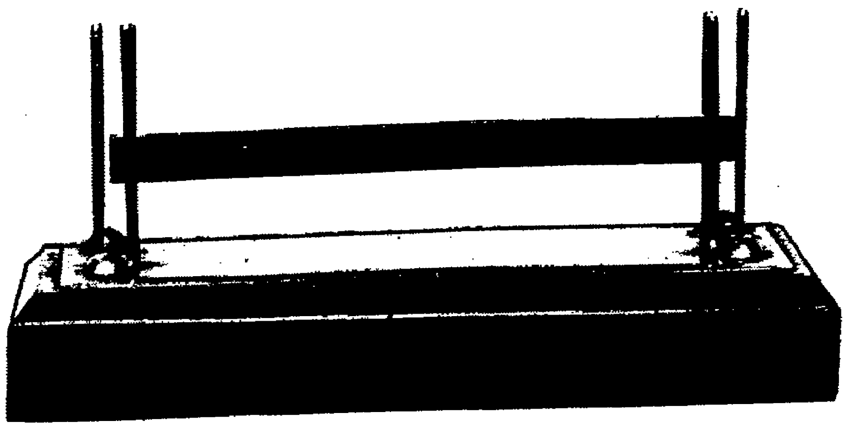
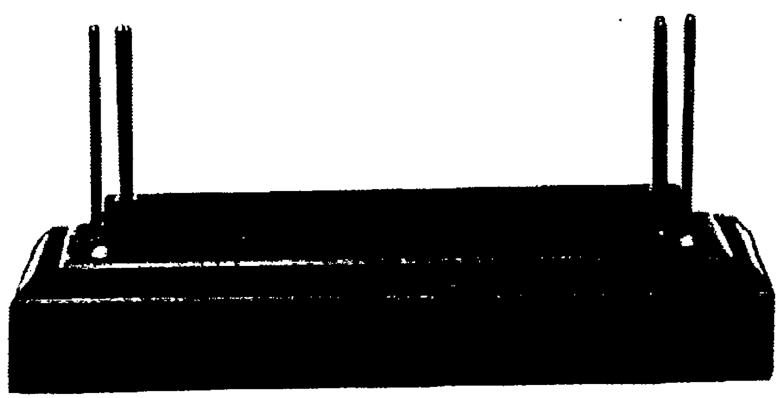


Fig. 39. The sound-track on the side of a cinematograph film. The track is shown enlarged on the left

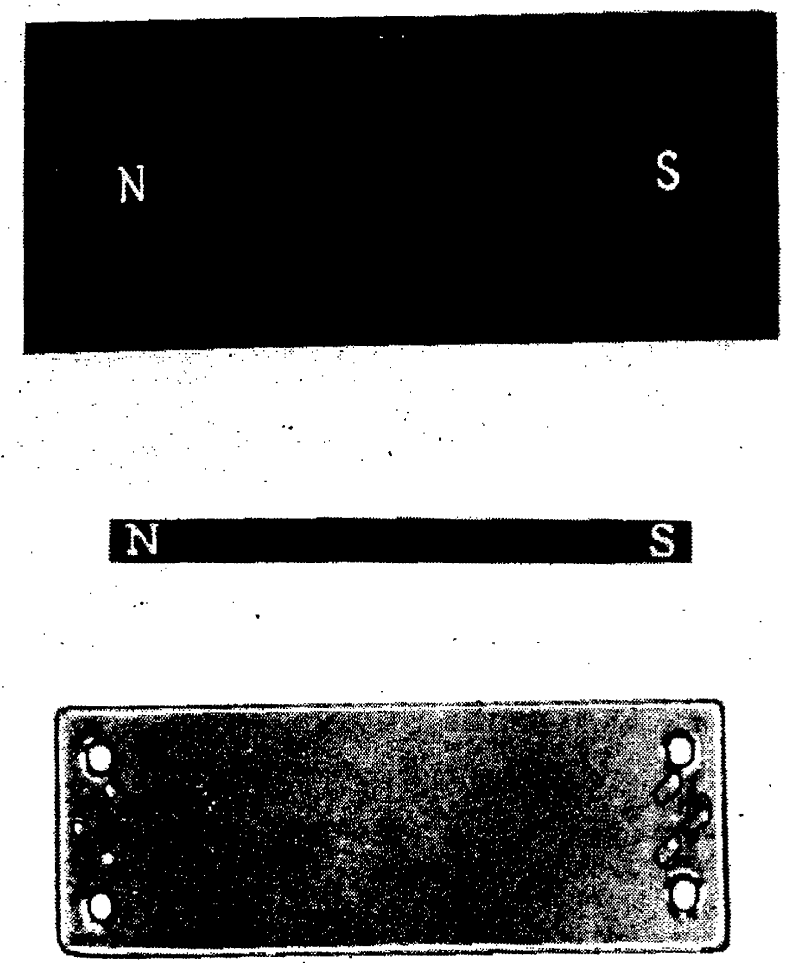
PLATE 10



(a)



(b)



(c)

Fig. 43. The 'Wobbly Bar.' The magnet is held suspended in the air by the repulsion of another magnet concealed beneath the metal base plate. This plate is removed in the photograph on the right. (*Bell Telephone Company, N.Y.*)

CHAPTER III

MOTORS AND DYNAMOS

1. MAGNETISM

In the first two chapters we have considered the behaviour of electrical charges, and the way in which these charges run from one place to another as electrical currents. In the present chapter we will consider the relation between electricity and magnetism, or to put it more precisely, the relation between electrical currents and magnetic fields.

Magnetic attraction was a great mystery and source of speculation in ancient times, like electrical attraction. The ancients were acquainted with two main ways in which it showed itself. A certain iron mineral called magnetite (Fe_3O_4) has the power of attracting iron objects, and stones which showed this property were called loadstones, because as we shall see they could be used to 'lead' or point the way. A famous ancient source of these stones was a place called Magnesia in Asia Minor, hence the name 'magnet.' If a piece of steel is rubbed with a magnet such as a loadstone, it becomes a magnet itself; magnetized bits of steel were called 'artificial' magnets in contrast to the 'natural' magnets, i.e. loadstones. Further, if a loadstone or an artificial magnet is suspended by a thin thread or put on a float in a basin of water, it sets itself so that one end points north and the other south. This property was known to the Chinese at least 3,000 years ago, and their historical records contain a reference to the use of what

appears to be a compass, or 'chariot of the South,' as far back as 2600 B.C. In the story called 'The Joyous Venture' in Kipling's *Puck of Pook's Hill*, the adventurers in the Viking ship were guided by a magic box which belonged to a yellow man (Chinaman). An iron needle suspended in the box was the abode of an evil spirit which was always straining to return to the south whence the yellow man had brought it by magic. A knowledge of the compass was beginning to leak through to barbaric Europe from civilized China, and was helping sailors to make bolder voyages on the open seas.

A piece of steel which has become magnetized has undergone some change which gives opposite properties to its two ends. For the experiments I am about to describe, we want a compass and a 'bar' magnet or straight piece of steel which has been magnetized, not one of the U-shaped magnets familiar to all (horseshoe magnets). Fig. 41 shows a bar magnet hung up by a stirrup of paper and a thread. If there is no twist in the thread the magnet points north and south. The end which points north is called the 'north pole' of the magnet and may be marked with an N or painted red. The other end is the 'south pole' and is marked with an S or painted blue. A compass has got a similar bar magnet fixed underneath a round pivoted card, with its north pole under the large arrowhead on the card. If now the magnet is brought towards the compass needle, the latter will become agitated and twist round. If the magnet's N pole is brought towards

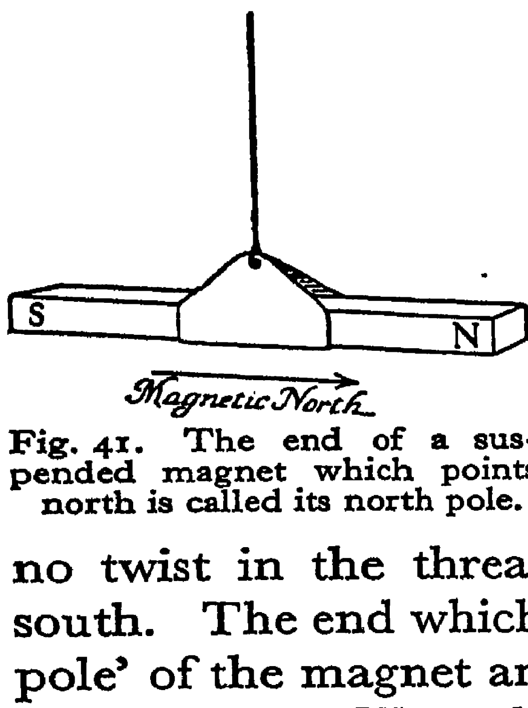


Fig. 41. The end of a suspended magnet which points north is called its north pole.

the compass, the S pole of the compass will strain towards it as if attracted, while the N pole will be repelled. If the magnet is turned end for end, the compass needle will reverse, the end which previously was attracted being now repelled. We can soon satisfy ourselves that

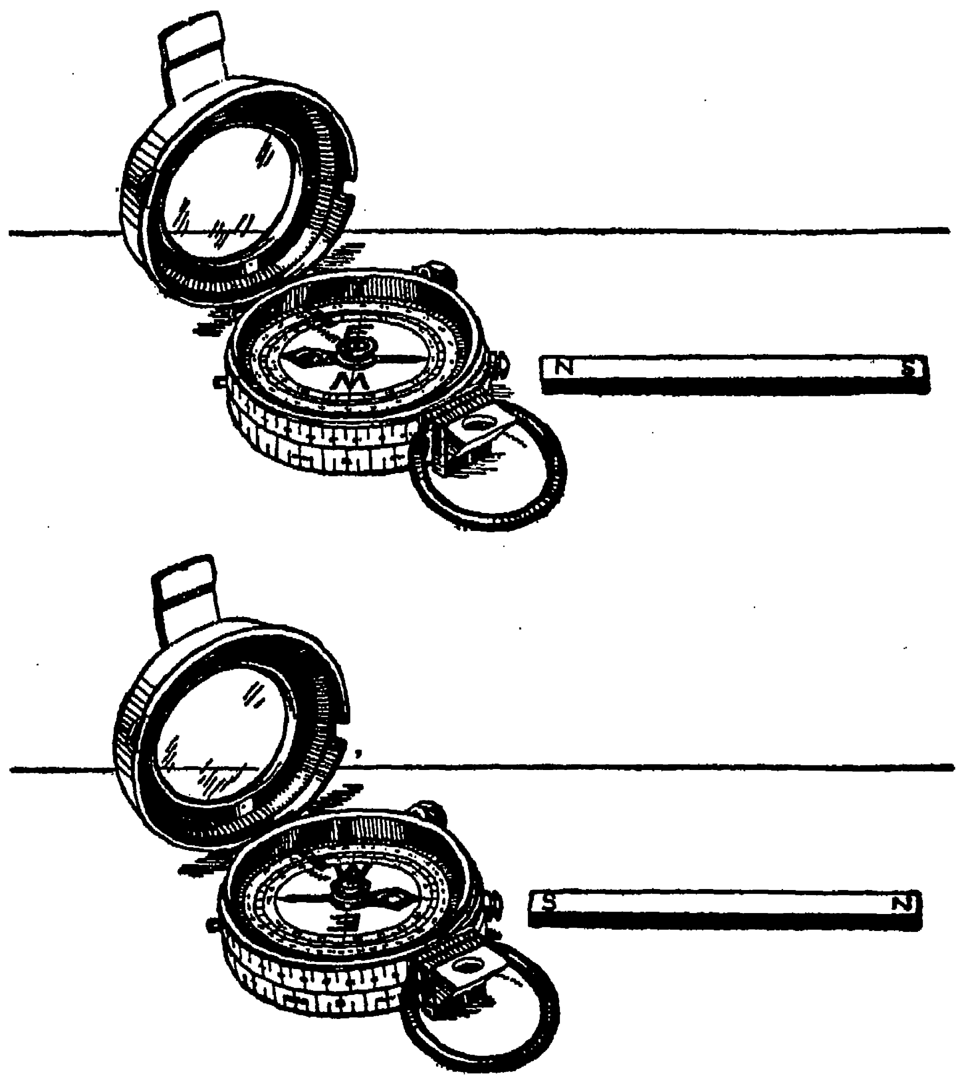


Fig. 42. Like poles repel each other, unlike poles attract each other.

north repels north, south repels south, whereas north and south poles attract each other. (See Fig. 42.)

The attraction and repulsion are vividly shown by a toy called the 'Wobbly Bar' which is made by the Bell Telephone Company in America, and which is photographed in Fig. 43*a* (Plate 10). All that one can see is a small bar of steel which appears to be

floating in the air in a miraculous way over a wooden baseboard with nothing to hold it up. The three pins at each end seen in the photograph do not support the bar, they only restrain its movements sideways or endways. If one presses the bar down, it promptly jumps up again and after a few wiggles comes to rest well above the baseboard. The secret is that the bar of steel is a magnet, and a similar magnet is concealed in the baseboard. The two north poles and two south poles are opposite each other (see Fig. 43*c*, Plate 10), and their repulsion is so strong that the upper magnet floats in the air. The trick is possible because both magnets are made of a kind of steel which can be very strongly magnetized. If one turns the upper magnet round so that N comes opposite S and S opposite N, it is drawn down towards the baseboard with considerable force as shown in Fig. 43*b* (Plate 10).

Magnetic attraction and repulsion remind us very much of the way in which like electrical charges repel each other and unlike charges attract, but there is an important difference. North and south poles always go together. We cannot charge a piece of iron with 'north magnetism' in the same way that we charge a conductor with positive electricity. We can only make one end of it north and the other south; it is as impossible to have one without the other as it is to have a rod with only one end.

The world itself behaves as if it were an enormous but weak magnet; that is why the compass needle points north and south. Since north attracts south, we must say that the world behaves as if a magnetic *south* pole were near the place marked *North Pole* on the map. This confusion is due to an unfortunate

choice for the names of the opposite ends of a magnet, but it is too late to alter them now.[1] The world's magnetic effect is not quite symmetrical; a compass needle deviates from true north and south by an angle which differs from place to place and alters slowly from year to year.

The direction in which a compass needle sets itself is called the 'direction of the magnetic field' at that point. The stronger the magnetic field, the greater is the force twisting a compass needle into the parallel position. Magnetic fields are measured in units called 'Gauss.' The earth's field in England is rather less than $\frac{1}{5}$ gauss, whereas that near a powerful electromagnet may be as much as 30,000 gauss.

It is perhaps worth while considering somewhat more carefully at this point the attraction of a magnet for a piece of iron. We have seen that north and south poles attract each other, but a piece of iron is attracted even if it originally has no magnetic poles. It acquires poles when the magnet is brought near it. The part of the iron nearest the N pole of the magnet becomes a S pole, and the far end a N pole. Since the S pole is nearer the magnet, its attraction is stronger than the repulsion of the N pole at the far end of the iron, and the iron flies to the magnet. You will probably have noticed the way in which a magnet seems to hand on its magnetism to a piece of iron which is sticking to it. We can stick one nail to a magnet, and another nail to that, and so on till a chain of half a dozen nails is hanging from a pole. Each nail becomes a magnet itself owing to the field of the large magnet.

[1] This difficulty is sometimes overcome by referring to what we have called the north pole of a magnet as the 'north-seeking' pole.

Another way of putting this is to say that the piece of iron always tends to move from a place where the field is weak to one where it is strong, the field being of course stronger near the magnet. In a uniform field, the iron does not move as a whole one way or the other, it only tends to set itself with its long axis parallel to the field. If we put some bits of iron on floats in a basin of water, they will not start drifting towards the north pole, because the earth's field at any one place is effectively uniform. I remember, however, a wonderful story in the *Boy's Own Paper* in the days of my youth, where this really happened. The people in the story ventured too far north in their voyage and finally got so near the North Magnetic Pole that all the nails were pulled out of their ship, which sank, and they went off hurtling through the air dragged by the iron of the muskets slung on their backs. If I remember rightly they were saved by Eskimos, who fortunately had canoes fastened together with sinews. In this story, fiction was stranger than truth.

Magnetic forces, and the relations between electrical currents and magnetic fields, are as mysterious and unlike any mechanical forces as they can well be. For this reason they are difficult to follow, and it is hard to get a conception of them into one's head, as I emphasized in the Introduction. Again it must be admitted that they cannot be explained but must be accepted as part of the fundamental behaviour of all things. We shall see that it is impossible to separate electricity and magnetism. They are the same thing seen from different points of view, or, to put it in another way, they are both names for the way in which everything behaves when we examine sufficiently closely.

I have headed this chapter 'Motors and Dynamos' but it is really about the electrical and magnetic effects by means of which motors and dynamos work. A knowledge of these effects is part of the electrical common-sense which we are trying to acquire.

2. THE CREATION OF MAGNETIC FIELDS BY ELECTRICAL CURRENTS

We now come to another of the great discoveries in the history of electricity and magnetism, standing out from the rest and opening up vast new fields, like the discovery of America by Columbus. In 1820, twenty years after Volta invented his pile, a Dane called Oersted discovered that an electrical current exerts a force on a magnet in its neighbourhood. People had previously attempted to find some connection between electricity and magnetism, but they had tried the experiments with charged bodies, or with the poles of a battery on open circuit. It was left to Oersted to show that the electrical charge only affects the magnet when it is *moving* past the magnet, or, to put it in another way, the magnet is only affected when a current is flowing along a conductor near it. The story goes that Oersted discovered the effect when he was lecturing to a class upon electricity and magnetism. In the course of the lecture it occurred to him to try the effect of putting a magnetic needle near a wire which connected the poles of a voltaic battery, and he found that the needle tended to set itself at right angles to the wire. Fig. 44 illustrates Oersted's experiment. To show the effect in a decisive way, we take a long straight conductor and pass a strong current of about five amperes through it. If the current is flowing from

left to right as shown by the arrow, and the wire is held above the needle, its north pole twists *away* from the observer. If the same wire is held underneath the needle, the north pole twists *towards* him. The effect is conveniently remembered by a rule due to Ampère. If we imagine our body to be a conductor in which current is flowing from the feet towards the head, then

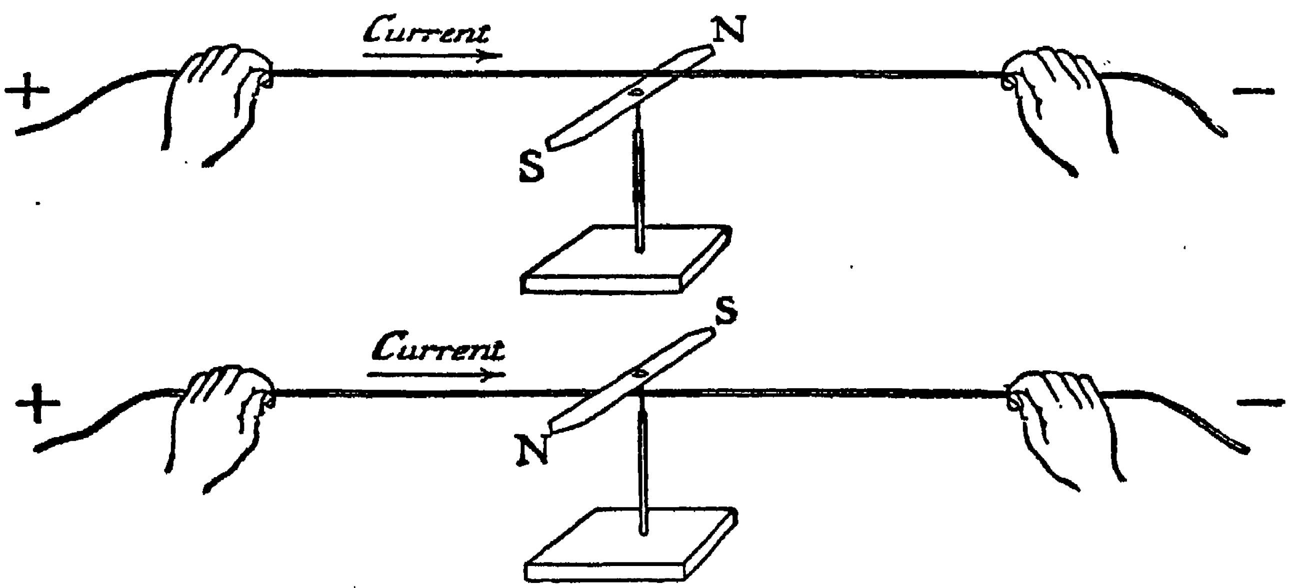


Fig. 44. The effect of a current upon a compass needle.

a north pole in front of us is deflected to the left, and a south pole to the right.

This is surely the most curious and twisty of all the fundamental forces of nature. The complicated rule for describing it reminds us of the way the old lady told the time by her clock: 'When the hands stand at half past seven and it strikes three, I know it is twenty to nine.' The pull of gravitation, and the attractions and repulsions of charged bodies, act *along* the line joining the bodies. This force acts *at right angles* both to the direction of the current and to the line joining the conductor to the magnet. The current creates a magnetic field the direction of which we must describe by drawing circles around the wire, not lines radiating from it.

Suppose we now take the same wire and bend it into a loop around the needle as in Fig. 45. If you remember the rule, you will see that the current in all parts of the loop has the same effect on the needle, making its north pole point away from us and the south pole towards us. The current in the loop makes a magnetic field run through the loop. An obvious next step is to increase the effect by making the current run around a coil consisting of a large number of loops. The effects of the loops add together and we get a much more powerful magnetic field.

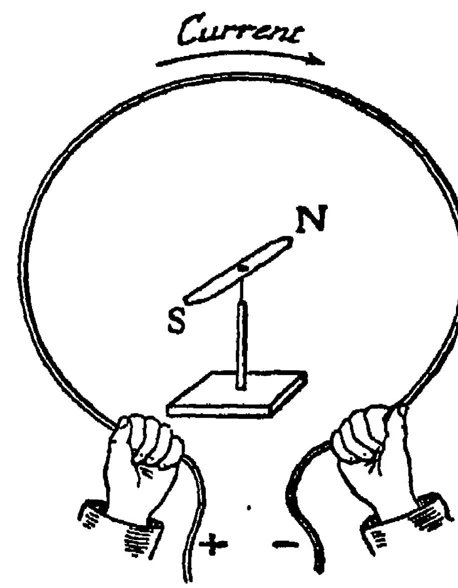


Fig. 45. The magnetic field inside a loop round which a current is flowing.

We need some way of representing a magnetic field in a diagram, and this can be done by means of magnetic lines of force, in just the same way that the electric field was mapped in Chapter I. The compass needle always points along a line of force, and the field is strongest where the lines are crowded most closely. By convention we take the direction of the lines of force to be that in which the N pole points, and this is shown by arrows in the diagrams. You will see in Fig. 46*a* the effect of a current in a straight conductor. Since the needle always sets itself at right angles to the wire, the lines of force are rings around the conductor. In (*b*) we have bent the conductor into a loop. The lines run through the loop and circle back outside. In (*c*) we have made several loops. The lines run in the same way, but the field is much stronger as indicated by the increased number of lines. Finally in

(*d*) the wire is coiled into a long corkscrew, called a *solenoid.* The lines of force come out of one end, run round outside, and into the other end again. What I wish you particularly to notice is that the lines of force produced by such a solenoid are just like the lines of force due to a magnet (*e*). The lines of force due to a bar magnet can be mapped out by laying a powerful

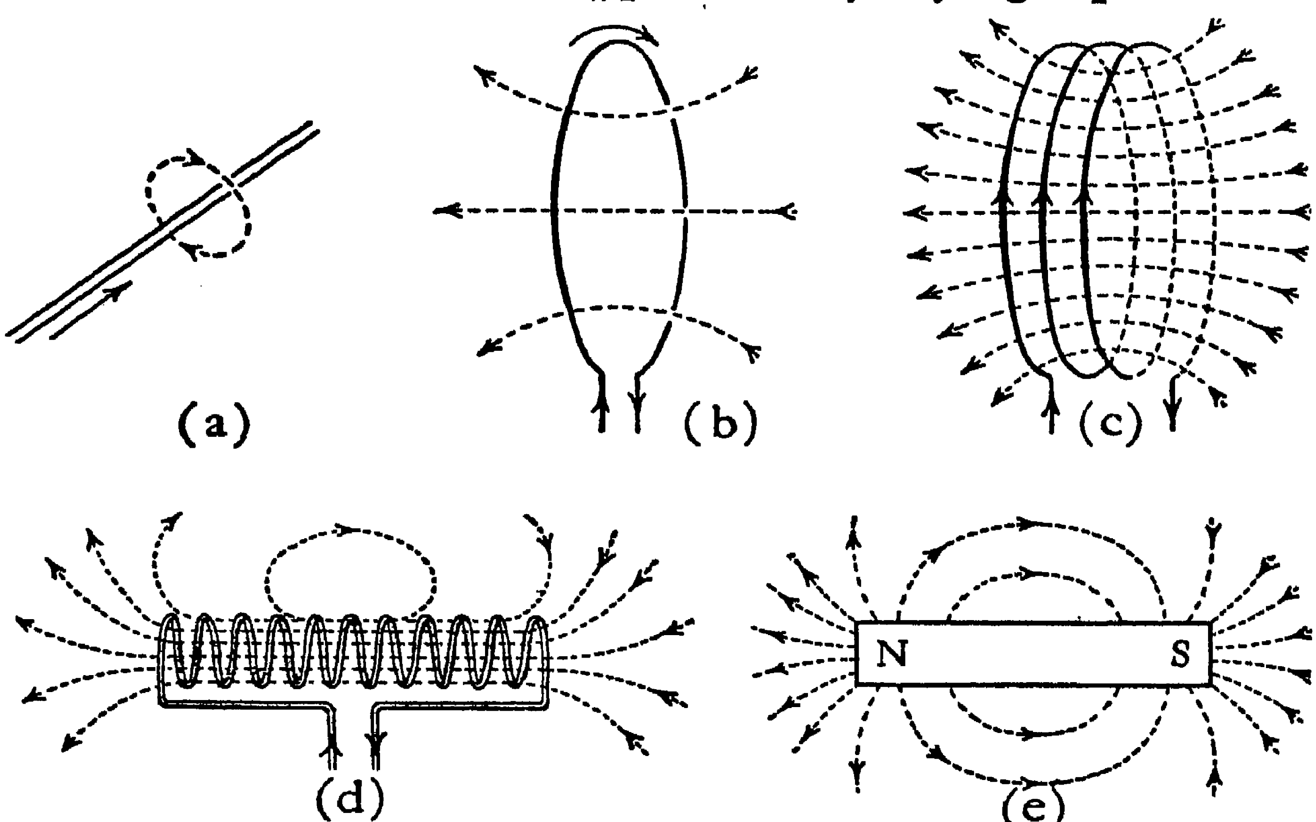


Fig. 46. Magnetic fields, due to currents, shown by means of lines of force.

permanent magnet on a sheet of paper, placing a small compass at various points near it, and drawing lines so that they are always parallel to the direction of the needle at each point. Since lines of force are a graphic way of describing magnetic effects, this means that *a solenoid carrying a current behaves just like a magnet.* It was the great French physicist Ampère who first showed this to be the case, only three months after Oersted's announcement of his discovery. Ampère went on to make the brilliant suggestion that a magnet

owes its property to its containing minute currents of electricity whirling round inside the steel molecules. These currents are always present, but ordinarily their circuits are tilted in all directions so that on the average their effects cancel out. When the steel is magnetized the circulating currents are twisted round so that they rotate in the same direction. Ampère saw, in fact, the connection between electricity and magnetism. He realized that magnetism is not a thing of a separate

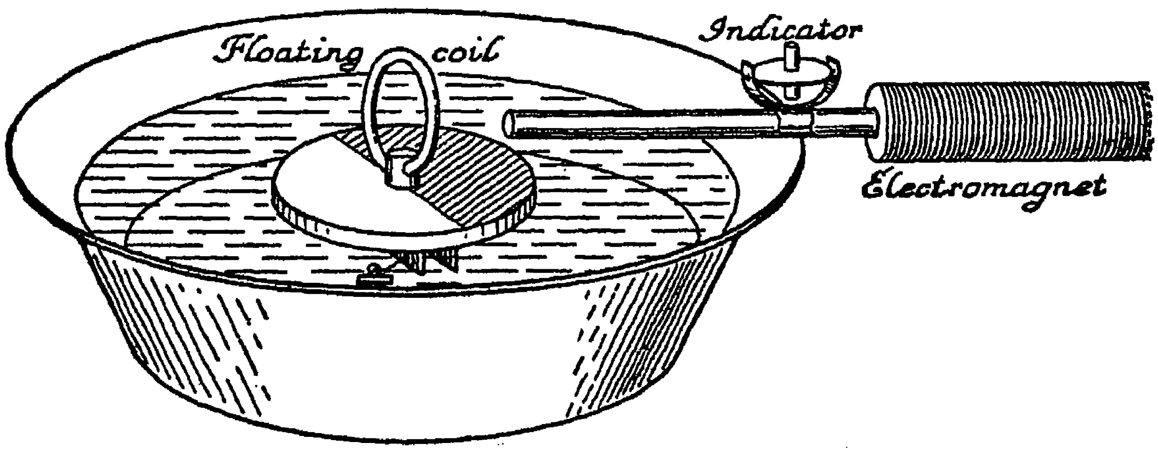


Fig. 47. A floating coil carrying a current is attracted or repelled as if it were a magnet.

kind, distinct from electricity, but that it is a name for the effects of moving electrical charges.

The experiment in Fig. 47 illustrates the behaviour of a coil carrying a current. The coil of fine insulated wire is mounted on a wooden float. Its two ends are connected to plates of zinc and copper beneath the float, which is placed in a basin of slightly acidulated water. The plates form a battery which drives a current through the coil, causing it to behave like a short electromagnet with N and S poles at opposite faces. Alternatively, a small dry battery can be used for this purpose. A powerful electromagnet (see next section) projects over the edge of the basin. If the current in the electromagnet is switched on, and its end

becomes a north pole, the coil will rotate so that the face representing its south pole is opposite to that of the electromagnet, and will then drift towards it and thread itself on to it. If now the current in the electromagnet is reversed, the coil will majestically move away, turn round, and thread itself on the pole the other way round. It is a fascinating experiment, because the coil

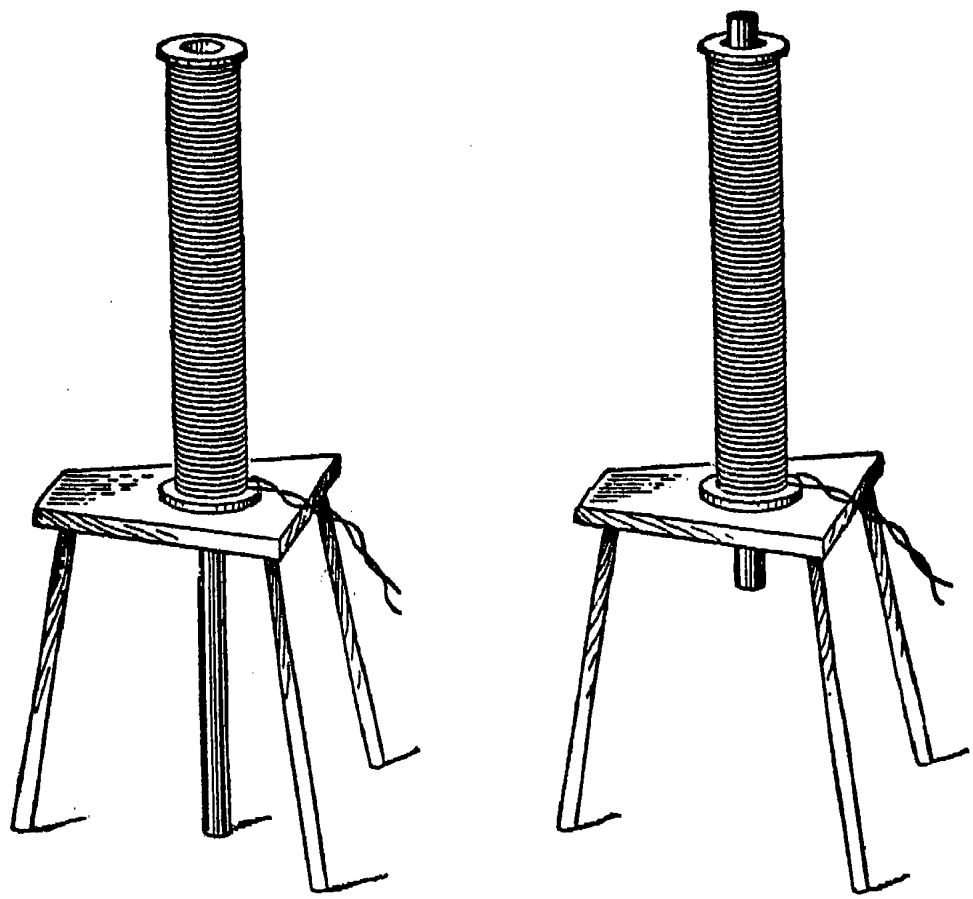


Fig. 48. When a current is passed through the solenoid, the iron pipe is sucked up into the magnetic field inside it.

seems to do it so cleverly. If you try this experiment, here is a tip worth remembering. If the float touches the side of the basin it is apt to stick to it by capillary attraction. This can be overcome by anchoring the float to the centre of the basin by a thread and small weight. The thread is long enough to allow the coil to perform its evolutions, but just too short to allow the float to touch the edge.

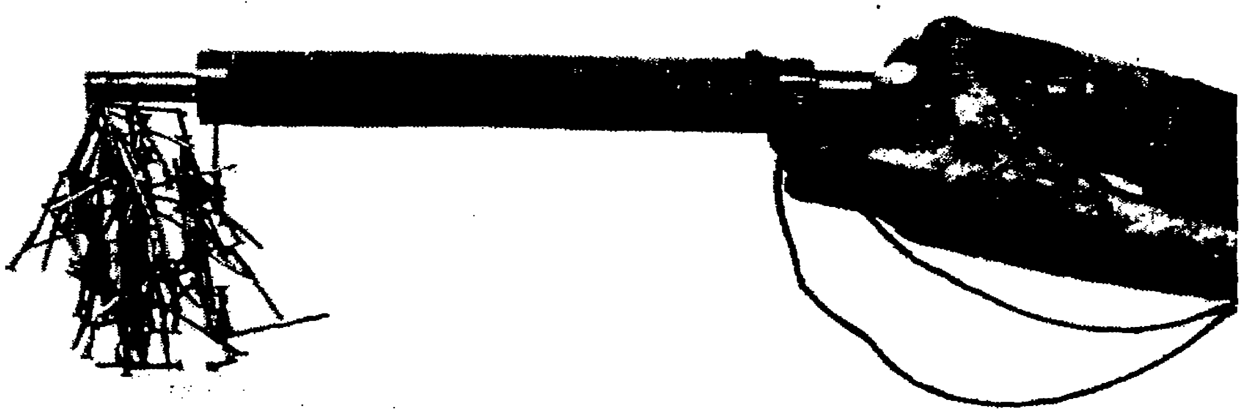


Fig. 49. Nails suspended from an electromagnet.

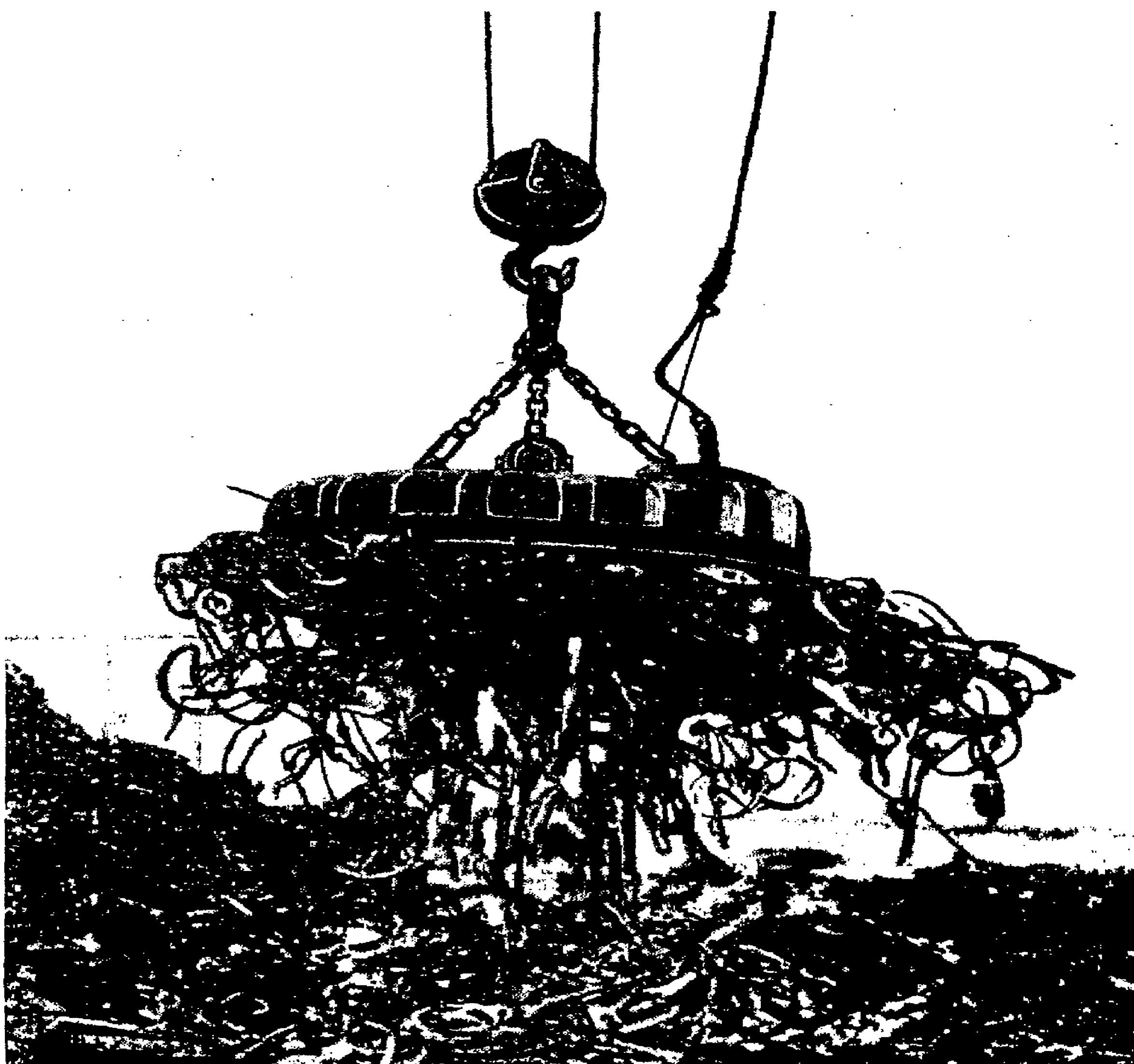
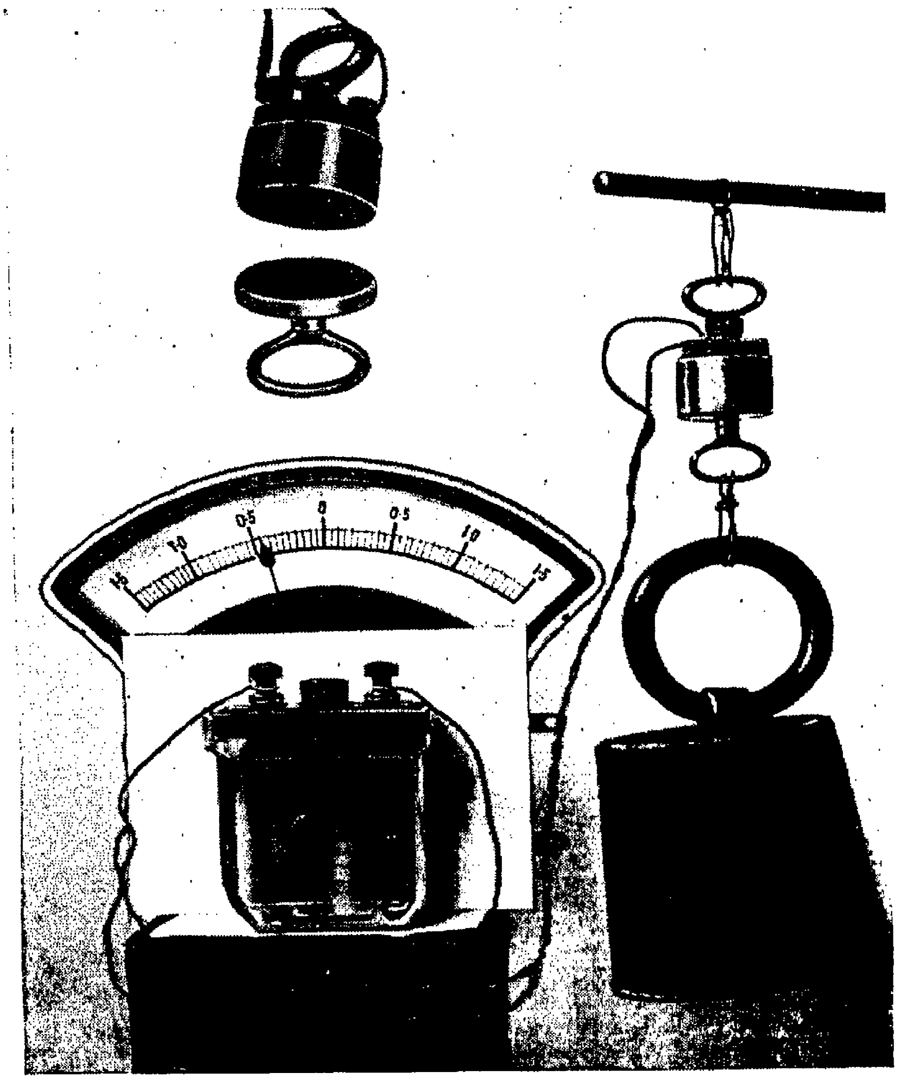


Fig. 50. An electromagnet on a crane, lifting scrap iron.
(*Rapid Magnetting Machine Company*)

[*p*. 108

(b)



(a)

Fig. 51. Small electromagnet supporting 56 lb. weight. One pole of the magnet is an inner iron rod surrounded by the coil, and the other is the outer iron casing

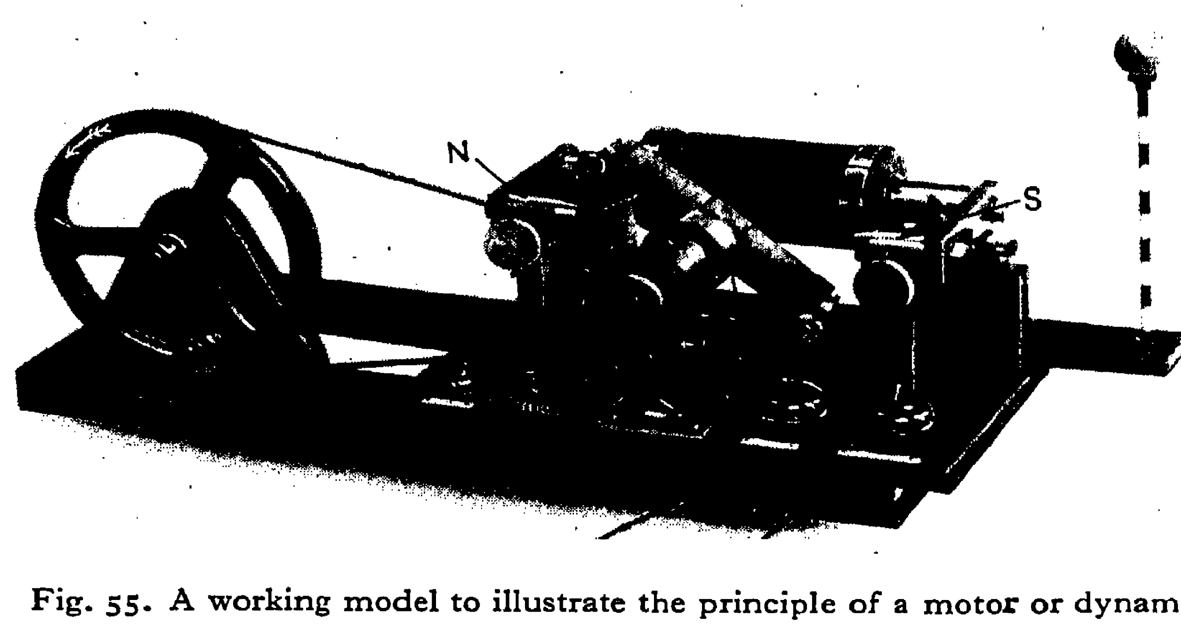


Fig. 55. A working model to illustrate the principle of a motor or dynamo

Fig. 48 shows a graphic way of demonstrating the field inside a solenoid. An iron pipe about three feet long rests on the floor, with its upper end just inside the solenoid which is supported on a stool. When a current of several amperes is passed through the coil, the iron pipe is drawn up and remains suspended inside it, falling to the floor again when the current is switched off. It is being drawn up into the strong field.

Electromagnets. If a bar of soft iron is put inside a solenoid in which a current is running, it becomes a powerful magnet. 'Soft' iron seems rather a misnomer, for all iron generally strikes one as being rather hard! Iron which is nearly pure and contains less than 0·1 per cent carbon in particular, is called soft iron, being easily hammered into shape and bent. On the other hand, iron containing more carbon (0·5–1·5 per cent) becomes springy and hard, and is called steel. One must hasten to say that these original names have very little meaning nowadays, for iron is mixed with many other metals, to give it various desirable properties, and the mixtures are called steels. It is possible to make electromagnets which are far more powerful than any permanent magnet. Fig. 49 (Plate 11) shows a straightforward type of electromagnet made of a straight bar of iron with a stout wire coiled round it. The wire is covered with insulation made of tape or cotton and rubber, so that the current flows along it and does not take short cuts between the turns. The magnet in the figure has been dipped in a pile of iron nails and then lifted; you can judge how strong it is from the number of nails which it picks up. Fig. 50 (Plate 11) shows an electromagnet on a crane, used to

pick up pieces of scrap-iron. When the current is switched on the iron sticks to the magnet, and when it is switched off the lumps drop off again. Fig. 51 (Plate 12) shows a tiny electromagnet, so small that it can be put in one's pocket. Yet when the current from an accumulator cell is passed through its windings, it can hold up a 56-lb. weight. The weight is attached to a ring on a small piece of soft iron which fits snugly to the poles of the magnet and so gets the full force of attraction (Fig. 51*b*). Finally, you will see in Fig. 52*a* (Plate 13) an enormous magnet made for Professor Blackett of Birkbeck College. This magnet weighs 11 tons and is used for experiments on cosmic rays. The pipes leading from the top of the coils are ducts for the air stream which cools the coils. Fig. 52*b* shows the plan of the magnet. Much larger magnets have been built in other laboratories for experiments which have to be carried out in very strong magnetic fields.

The soft iron core of an electromagnet is strongly magnetized as long as the current is running, but loses practically all its magnetism when the current is switched off. On the other hand, a piece of steel is not so strongly magnetized in a solenoid, but retains a high proportion of its magnetization when the current ceases. Permanent magnets are made by placing a bar of steel inside a coil through which a strong current is passed. If ever you are doing experiments with strong magnets, or go near a big dynamo in a power-house which has a strong field magnet, it is wise to remove your watch and leave it at a safe distance. Otherwise the steel parts will get magnetized, and the watch will keep bad time owing to forces on the hair spring. Strong permanent magnets are required for the magnetos of

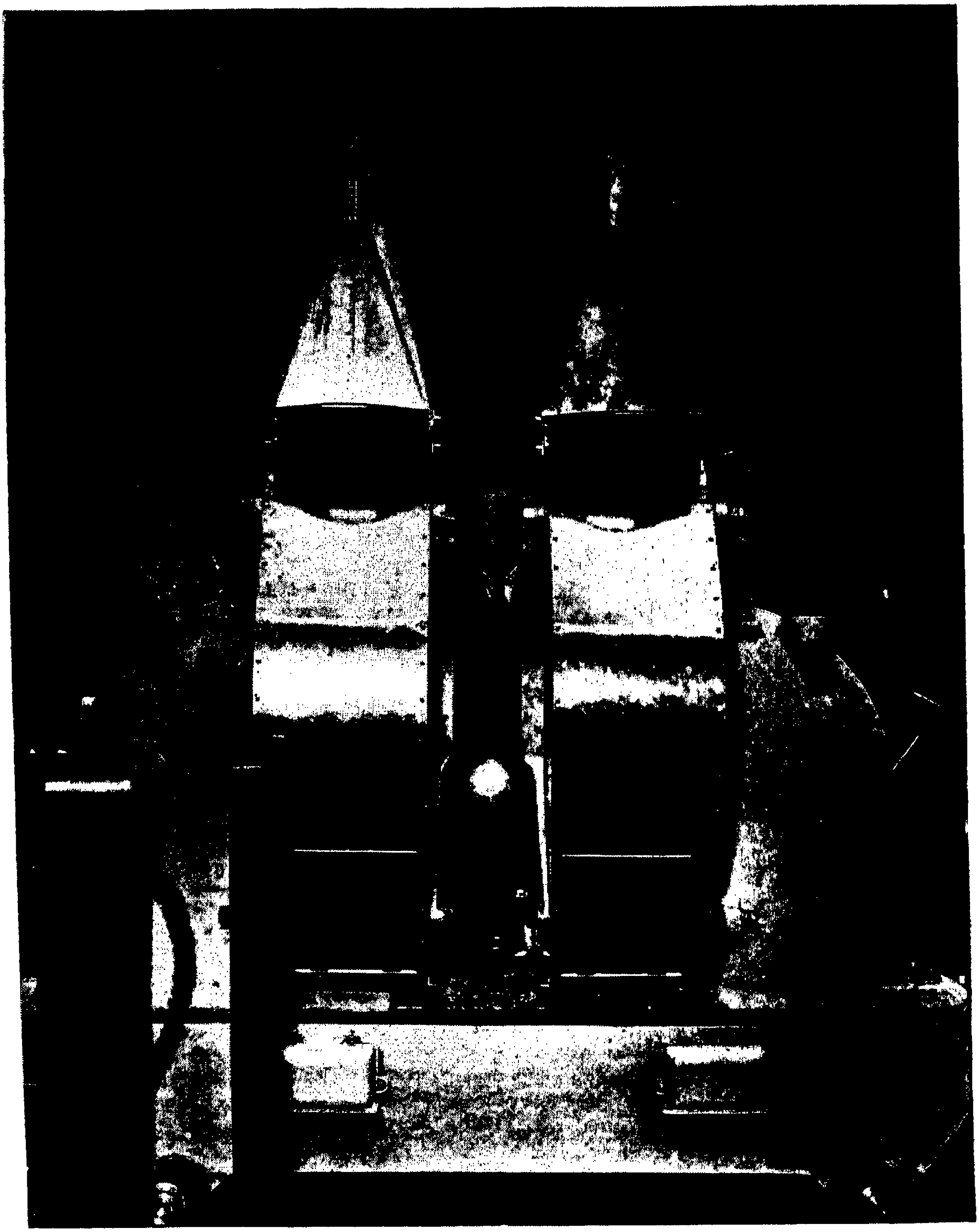


Fig. 52*a*. A large electromagnet for experiments on cosmic rays.
(*Metropolitan-Vickers*)

[*p*. 111

internal combustion engines, and many investigations have been made to find a kind of steel which can retain the highest possible amount of magnetization. Cobalt magnet steel containing 35 per cent cobalt is

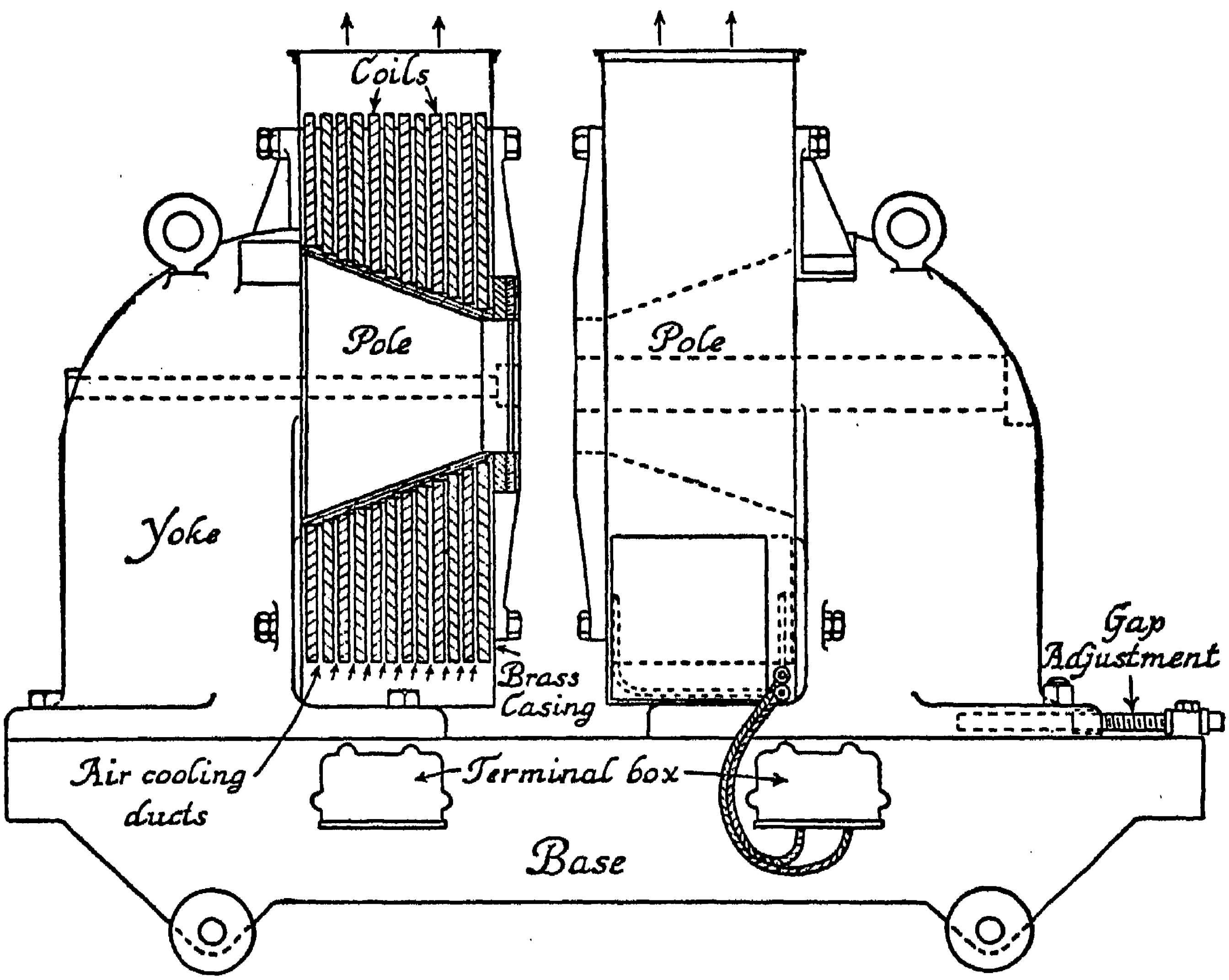


Fig. 52*b*. A plan of the large electromagnet shown in Fig. 52*a*.

widely used. An even better alloy which has recently been discovered contains iron almost free from carbon alloyed with 25–30 per cent nickel, 12 per cent aluminium, 5 per cent cobalt, and 3 per cent chromium.

3. AMMETERS AND VOLTMETERS

The most common types of instruments which are used to measure voltage and current depend upon the

reaction between a moving coil carrying a current and a fixed permanent magnet. Fig. 53 shows the construction of a Weston instrument.

A permanent magnet bent round so as to have a shape like a Moorish arch has two soft iron pole pieces fixed to its ends, with a cylindrical gap between them. A cylindrical core of soft iron is placed in this gap, leaving a channel all round. The soft iron core makes a suitable path for the lines of force between the poles so that the magnetic field in the gap is uniform. The pivoted moving coil with its attached pointer (Fig. 53*b*) surrounds the core and can turn freely in the gap. The current is led into and out of the coil by spiral springs at top and bottom. When a current flows through the coil, it tends to twist round against the springs so that its own magnetic field is in line with that produced by the permanent magnet (Fig. 53*c*). In a well designed instrument, the twisting force is almost exactly proportional to the current, so that the divisions of the scale on which equal steps of current are read are nearly uniform.

An instrument of this type will serve either as ammeter or voltmeter. When used as ammeter it is provided with a 'shunt.' We may require to measure a current of many amperes, and it is of course impossible to send this current through the windings of the delicate coil. The current mainly passes through a stout conductor or shunt of low resistance as shown in Fig. 53*d*. A fractional part of it takes the alternative by-pass through the much higher resistance of the ammeter, and since this part is always proportional to the main current it may be used to measure it. For instance, if the resistance of the ammeter is 999 times

as high as that of the shunt, a 10-ampere current will split up so that $\frac{1}{100}$ ampere goes through the moving coil,

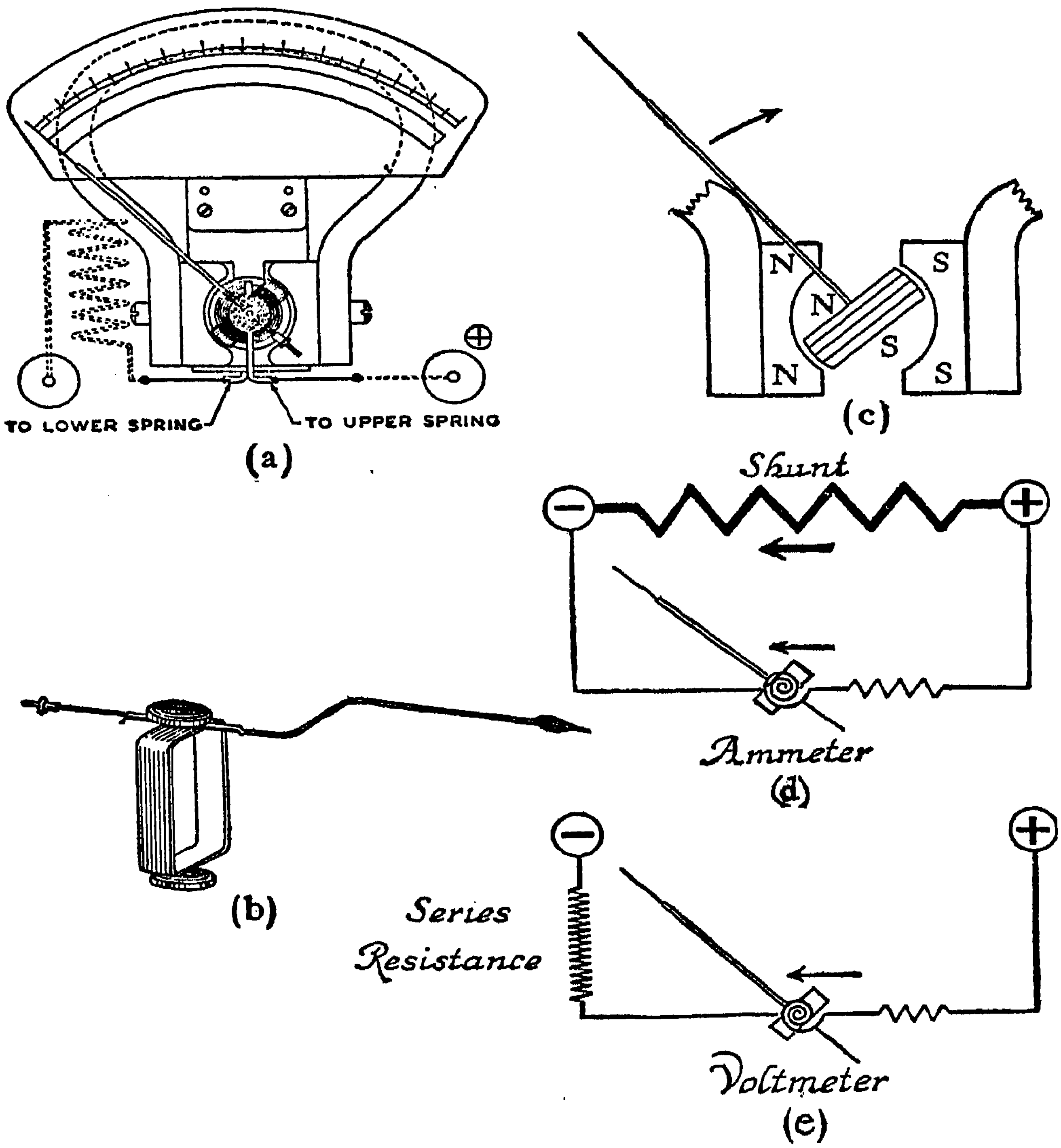


Fig. 53 *a, b, c, d, e.* Diagrams illustrating the construction of moving-coil ammeters and voltmeters. (*Weston.*)

which is of the right order to give a full deflection. It is common to provide the ammeter with alternative terminals, so that different shunts can be used, giving

it ranges from 0–1 amperes, 0–10 amperes, etc. The resistance of each shunt is adjusted so that the instrument reads correctly on the corresponding scale.

When the instrument is used as a voltmeter, a high resistance is placed in 'series' with the moving coil,

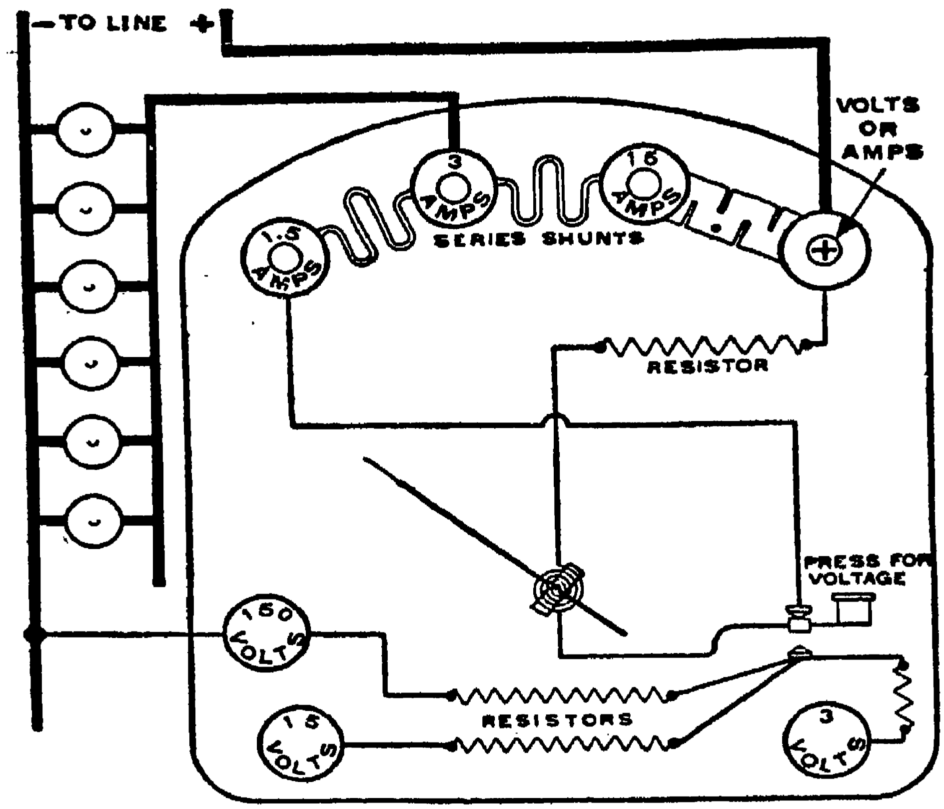


Fig. 53*f*. A moving-coil instrument with the following scales:
0–1.5 amps., 0–3 amps., 0–15 amps.
0–3 volts, 0–15 volts, 0–150 volts.
It is being used to measure the current (on 3-amp. scale) or voltage (on 150-volt scale) supplied to six lamps. (*Weston*.)

i.e. the voltage to be measured has to drive a current through the high resistance as well as through the coil, and the latter current is therefore very small (Fig. 53*e*). Provided the resistance is much higher than that of the rest of the circuit, the current flowing through the coil is a measure of the voltage. Again, by providing alternative resistances, the same instrument can be used for different ranges of voltage. Fig. 53*f* shows the connections in an instrument with a number of scales.

It is being used to measure both the voltage applied to a series of lamps and the current taken by them.

The coil is wound on a light aluminium frame. When the coil moves, 'eddy currents,' which will be described in the next chapter, are set up in the frame. These currents damp the motion of the coil and needle, which only makes a few oscillations before coming to rest, so that it is easier to read the instrument. I have described this typical moving-coil instrument in some detail, because voltmeters and ammeters are so important in any practical handling of electrical gear.

4. THE ELECTRIC MOTOR

An electric motor is driven by the attractions and repulsions between electromagnets; it has three essential parts. There is firstly a fixed electromagnet, called the *field magnet.* In small motors the round iron case itself generally forms part of this field magnet, so that the motor may be as compact as possible.

Next there is a rotating *armature* made of iron, with windings of insulated copper wire. The armature is magnetized by currents through these windings. It is mounted between the poles of the field magnet on a spindle passing through bearings. Finally there must be some way of getting the electrical current into the armature, and this is done (in the ordinary type of motor) by means of the *commutator*. The windings on the armature are connected to a series of copper bars arranged on a cylinder (see Fig. 54) and two blocks of carbon called the *brushes* press on these bars as the armature rotates. To call these carbon blocks 'brushes' seems curious; the name has survived from early days when a real brush of wire was used to lead the

current into the commutator. Carbon was soon found to be much better, because it wore away the commutator less quickly, but the name stuck, as so often happens. Fig. 54 shows the parts of a small motor which has been taken to pieces.

When current is supplied to a motor, the armature spins round and can be used to drive things. A motor enables us to convert electrical power into mechanical

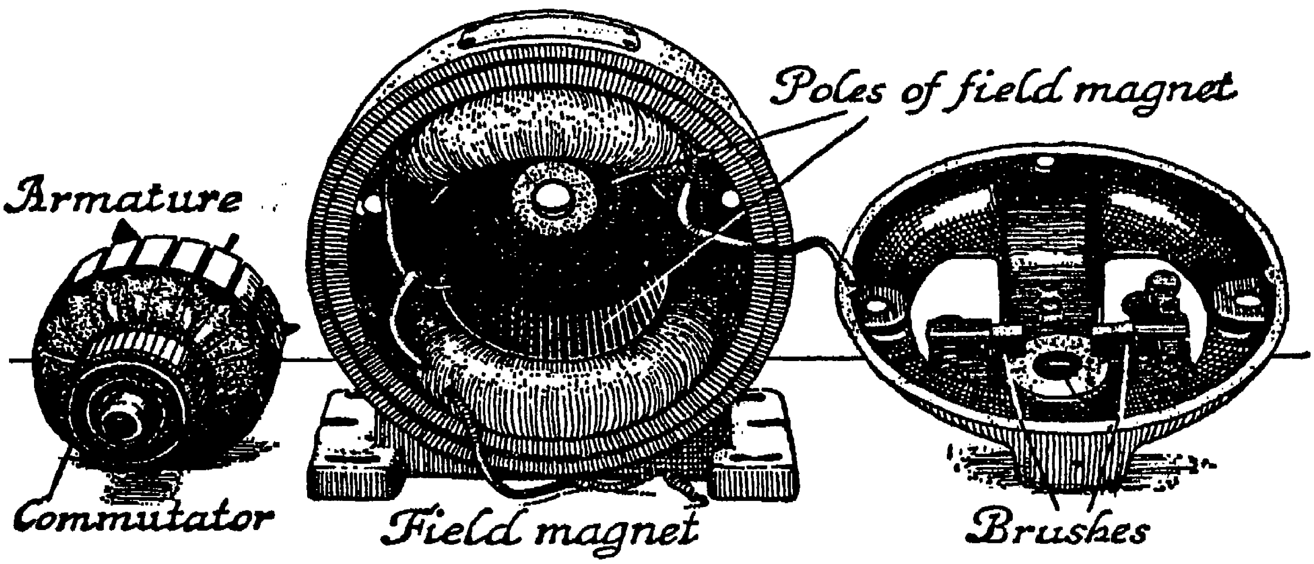


Fig. 54. The parts of a small motor, showing the field magnet, armature, commutator, and brushes.

power. The small motors which drive electrical fans or vacuum cleaners are familiar; tramcars have powerful motors mounted on the bogies at each end; in many factories each piece of machinery is driven by a separate electric motor instead of by the old system of belts coming from an overhead shaft. If you want to study how a motor works, however, the best for the purpose are the delightful miniature motors which are made for model boats and trains, because they are much simpler than the large motors and you can see their parts.

Fig. 55 (Plate 12) shows a photograph of a motor which we built for the Christmas lectures. It is a thoroughly bad motor as an engineering job, because

it gives little power and uses a lot of current. On the other hand, it is an excellent one for explaining how a motor works. You will see the big *field magnet*. The coil at the back magnetizes it, and makes the two pole pieces North and South as marked in the figure. One must get accustomed to the way in which the lines of force follow a path through iron wherever possible. Even when the iron is bent round into a U shape as shown in the figure, a coil placed at one point magnetizes the whole U, and produces a strong field between the poles marked N and S; we need not have a coil wound round the whole of the U-shaped piece of iron. We made the *armature* as simple as possible. It is a straight bar of soft iron, with a coil wound round it, and is mounted on a spindle with just room to turn between the poles of the field magnet. The *commutator* is made from a cylinder of brass, cut by slits into two equal halves and mounted on an insulating bush. The two ends of the armature winding are brought to the commutator, and connected as shown in the figure. The *brushes* are two brass strips pressing on the commutator.

Fig. 56 shows how the current runs in the armature. Suppose we start with the armature as in Fig. 56*a*. Current enters by the right hand-brush, which presses on the one half of the commutator. From this it goes to the winding, runs round it and out by the other half of the commutator and the other brush. As a consequence (remember the rule about the magnetizing effects of currents) the left-hand end of the armature becomes N and the opposite end S. The N pole of the field magnet repels the N pole of the armature, and the two S poles also repel each other, so the armature

turns as shown by the arrow. In (*b*) it has got half-way. In (*c*) N and S poles are attracting and the armature is still pulled round in the same direction. If this were all, directly the ends of the armature passed the poles of the field magnet, it would be pulled

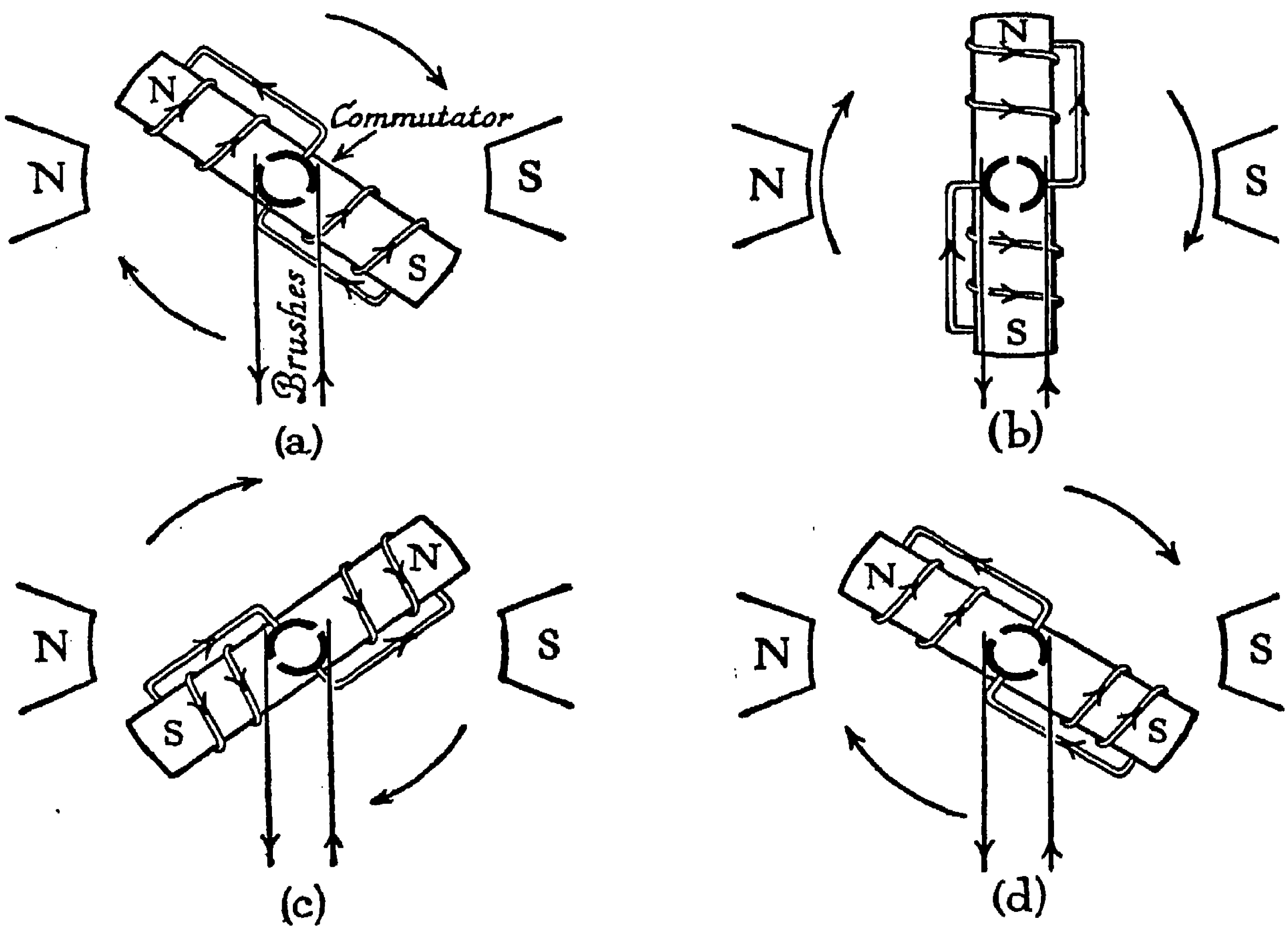


Fig. 56. Four successive positions of the armature of a motor, showing that it continues to rotate in the same direction.

back again. But this is where the commutator comes in. You will notice that as the armature moves a bit further, the brushes exchange connections in the commutator. The consequence is that the current starts running the other way in the armature, as shown by the arrows, and what had been its north pole becomes its south pole. It therefore *continues to turn round*, because the ends which were previously attracted by the field magnet poles are now repelled. The process

is repeated, for you will notice that (*d*) looks just like (*a*) so that everything happens over again.

It is just like the famous carrot in front of the donkey's nose. The carrot was really attached to the cart, so that, as the donkey moved forward to reach it, the carrot kept just in front of him. I remember seeing a film of Felix the Cat building a motor-car on similar principles. He captured a mouse and put it on a moving belt inside the bonnet. A piece of cheese hung just in front of the mouse, and when he tickled the carburetter the cheese danced about in an enticing way, the mouse sprinted along the belt, and off went Felix in his 'sports model.' In the electric motor, just as the armature makes the point where N and S poles are opposite the current is reversed and on it must go again.

We can follow these changes by means of little indicators as shown in Fig. 57. A small but very strong permanent magnet of cobalt steel is thrust through a round card. The card is painted red on one side to show north and blue on the other to show south, and is pivoted on a bracket which can be clipped to the poles of a magnet. When the pole of the magnet changes from N to S, the card turns over so as to show blue where formerly it showed red. Our motor had two such indicators on the poles of the field magnet and two on the poles of the armature. One could see the cards on the armature changing colour as the armature passed the field magnet poles. The indicators turn over so quickly that even when the armature is rotating quite fast one sees a streak of red above the field magnet poles and a streak of blue below.

A motor such as this moves in a jerky way because the poles attract or repel each other much more

strongly when they are close together. Real motors are built in such a way that the armature has effectively got many positions of the poles, and the commutator is correspondingly divided into many strips, as you will see by examining one (see also Fig. 54). The motor therefore works smoothly, just as a modern motor-car engine with eight cylinders is more smooth

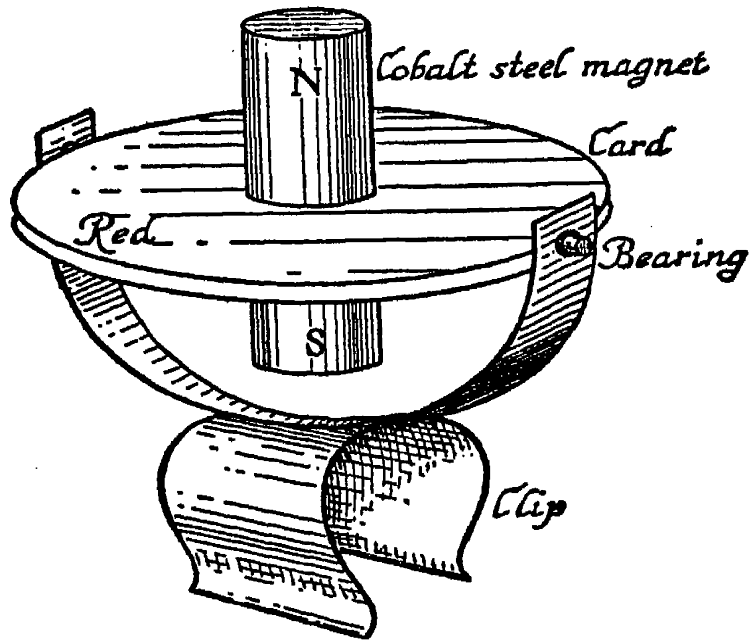


Fig. 57. An indicator of the polarity of a magnet.

than the one-cylinder engine of the first motor-cars. We get stronger magnetic fields if the path of the lines of force is made as short as possible. The field magnet is therefore made very compact, being just two short poles, with coils round them, fastened on to a circular iron block which often forms the outer case of the motor. For the same reason, the clearance between the armature and poles is made as small as possible, because the magnetic field is greatly weakened if the lines of force have to traverse a broad air-gap.

A motor illustrates very well the neatness of electrical machinery. Compare it with a steam or internal combustion engine with its pistons, cranks and valves, all

rubbing on each other and creating friction and wear. The only parts of a motor where friction occurs are at the commutator, where the pressure of the brushes is quite light, and in the bearings of the axle, which may be ball-bearings packed with grease which do not require attention for years. Its 'working parts' are merely magnetic attractions and repulsions. Motors are extremely efficient, turning very nearly all the electrical energy into available power.

5. THE CREATION OF CURRENTS BY MAGNETIC FIELDS

The crowning discovery of the relationships between electricity and magnetism was made by Faraday.

Tyndall says of Faraday that he 'was the greatest experimental philosopher the world has ever seen.' There is hardly any branch of electricity and magnetism in which he did not make fundamental discoveries, any one of which would have entitled him to the highest scientific rank. An exhibition was arranged in the Albert Hall in 1931 to celebrate the centenary of his discovery of electromagnetic induction. Faraday's original experiments were shown at the centre of the hall, with in many cases the apparatus which he used. Radiating outwards through the hall were exhibits showing the development of each of his great discoveries, ending finally in displays representing vast industries which have grown up as the result. His work on electromagnetic induction, or the creation of currents by magnetic fields, was his greatest achievement, and modern electrical engineering is based upon it.

There is another side of Faraday's genius to which perhaps we owe as much as to his power of finding new natural laws, and this is his way of thinking

about the discoveries which he made. We know far more than Faraday did. His early experiments with simple apparatus have been followed up by others more exact and profound. Faraday was no mathematician, and in the diary in which he kept a record of his experimental researches there are no equations with x and y, nothing but the simplest language and figures giving the measure of the effects he observed. Yet we consider his work as an example of all that is finest in science.

Faraday had a beautifully clear and simple way of gathering together and relating the facts he discovered. Perhaps I may illustrate what I mean by a humble example, that of being taught how to play a game by an expert. We have been making a stroke at cricket or tennis in a queer complicated way of our own, doing it in the most difficult manner, and rarely bringing it off. Then someone shows us how the stroke should be made. When we catch the knack it becomes gloriously simple, and can be brought off with the effortless ease which is called 'good style.' Exactly the same thing is true of *thinking*. Left to ourselves, we arrange our thoughts in a muddled way till we get so tied up in the tangle that we cannot go forward. Then someone puts the whole thing in a new way to us. We may know all the facts already, but he shows how they fit into each other and arranges our ideas. We become masters of ideas which had defeated us before, because we have been shown how to think clearly. There is 'good style' and 'bad style' in thinking, just as much as in playing a game. My work as a teacher of physics is not to tell my students facts, which they will get much more accurately from books than they will from

me, but to show them how to think about these facts. When I have succeeded in putting a point clearly, I can sometimes see a student grin appreciatively in spite of himself and of the grim surroundings of the lecture room, just because I have provoked the reaction, 'Of course if one looks at it in that way it is obvious.'

In its very highest form, this is what people like Faraday give to the whole world. We can all follow when a great genius leads, some of his power passes to us. We travel along a broad highway of thought when he had to blaze a trail through the tangle. All our ways of thinking about electricity and magnetism have been moulded by Faraday's influence.

The discovery which forms the title of this section may be summed up as follows. We have seen how we can produce electrical charges by friction, and cause a flash of current when bodies are discharged. In the next stage of advance, the voltaic cell made it possible to create currents which flow for a considerable time. The current is driven by chemical energy, due to the atoms inside the cell re-sorting themselves in a new way as the cell runs down. As long as currents had to be made in this way, they could never be very powerful. Expensive chemicals were used up in the batteries, and this limited their size. Faraday showed how to make a current run round a circuit, such as for instance a simple ring of wire, *without any battery to drive it.* This discovery is the foundation of all the developments of electrical power on a large scale.

The effect which Faraday discovered is called 'Electromagnetic Induction.' His first experiment was made with a ring of soft iron, around which he had wrapped two coils of wire (see Fig. 58). The ends of

the coil A were connected to a copper wire which passed just over a magnetic needle three feet from the coil. Any current in the circuit would be shown by a movement of the needle; the arrangement in fact was a simple form of *galvanometer*, an instrument for recording current. He then connected the ends of the coil B to a 'battery of ten pairs of plates.' On making the connection, the needle was deflected to one side, oscillated for a while, and came back to rest in its original position. On breaking the circuit, the first deflection of the needle was in the opposite direction and it then came to rest as before.

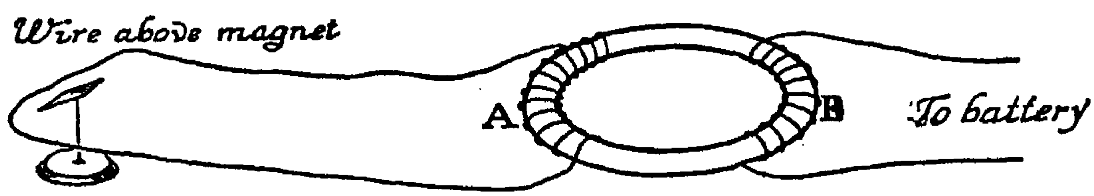


Fig. 58. Faraday's discovery of electromagnetic induction.

Faraday now made a series of experiments and showed that the results could be explained by the same general principle. Fig. 59*a* illustrates one in which a piece of iron on which a coil had been wound was placed between the poles of two permanent magnets arranged as in the figure. Each time the contact between the magnets and piece of iron was made or broken, an impulse of current was registered by the galvanometer. He next tried two coils of wire side by side as shown diagrammatically in Fig. 59*b*. When the current in one was made or broken, the galvanometer showed a momentary current in the other, so that it was clearly not necessary to have iron inside the coils. Finally, when one end of a bar magnet was thrust into a coil, or withdrawn from it, the same momentary currents were observed (Fig. 59*c*).

You will notice that in every case a current flows in one direction when the magnetic field inside a coil is being made stronger, and in the opposite direction when the field is being made weaker. It is only caused by a *change* in the field, for a steady field has no effect. In the experiment illustrated in Fig. 58, starting the current through the coil B magnetizes the iron ring

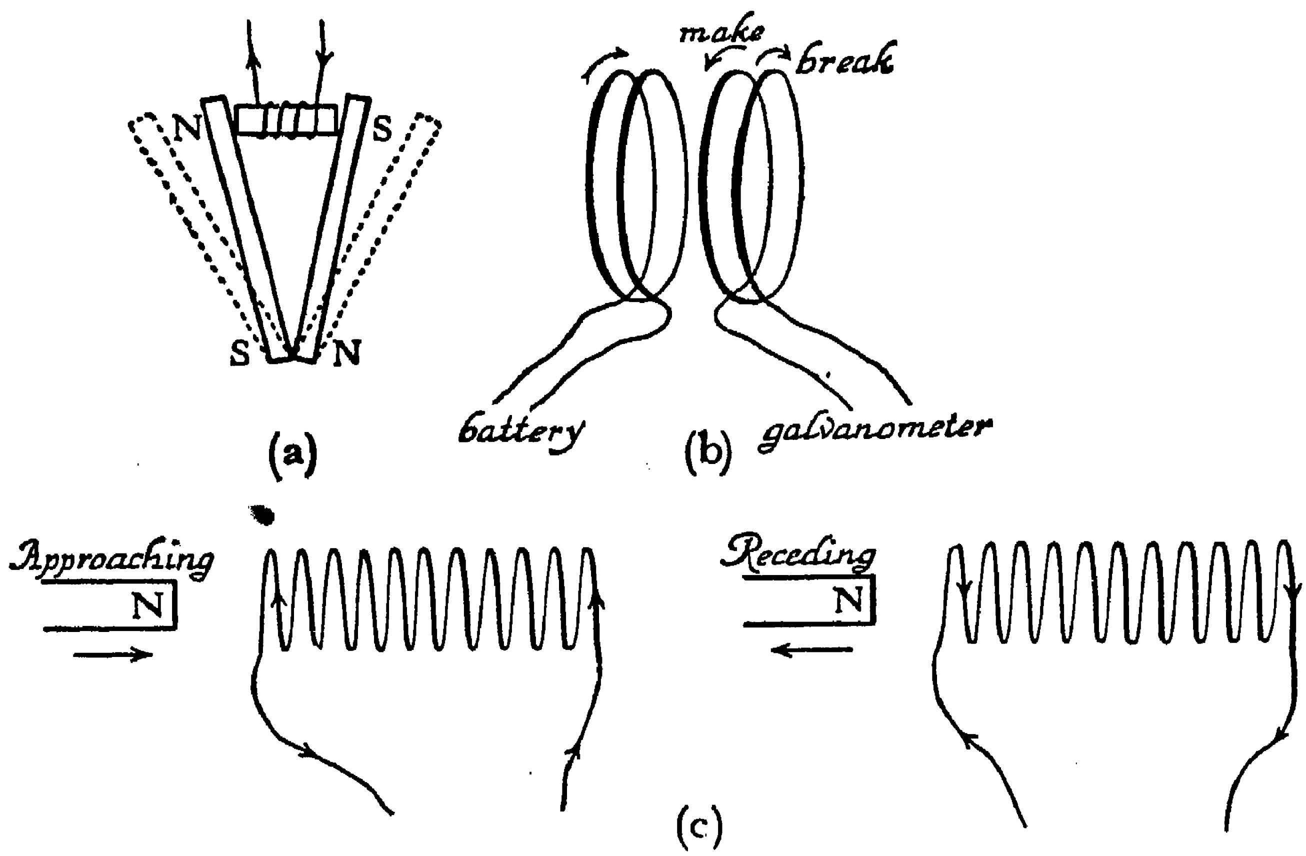


Fig. 59. Various ways of demonstrating electromagnetic induction.

and so alters the magnetic field inside A. This causes an 'induced' current in A. When the current in B ceases the ring loses the greater part of its magnetization and a current is induced in the opposite direction in A. In Fig. 59*a* the magnetization of the iron was reduced when the permanent magnets were withdrawn, and increased when they were brought into contact again. In (*b*) the magnetic field was created by the coil on the left when the current was allowed to pass and

disappeared when it stopped. In (*c*), in Faraday's own words, 'a wave of electricity was so produced from *mere approximation of a magnet*, and not from its formation *in situ*.' When the magnet is brought towards the coil the field in the coil increases, and when the magnet is withdrawn it again decreases.

Electromagnetic induction is the last of the four effects with which we must become thoroughly familiar if we are to acquire that 'electrical common-sense' to which I referred in the introduction. The effects form a symmetrical group. There are (1) the attractions and repulsions between electrical charges, and (2) the attractions and repulsions between the poles of magnets. We then come to the links between electricity and magnetism. A *stationary* electric charge has no effect on a magnet, but if electric charges are *in motion* as in the electric current, a magnetic field is produced (3). Finally, Faraday showed that, although a stationary magnet or constant magnetic field due to a steady current had no effect on an electrical charge, a *moving* magnet or *changing* magnetic field has such an effect (4). The changing field exerts a force on the charge, trying to drive it round a circuit as in the experiments we have just described.

6. THE DYNAMO

Electromagnetic induction makes it possible to create an electrical current by means of mechanical energy. At first sight it might appear as if we were getting an electrical current for nothing in such an experiment as is shown in Fig. 59*c*. Just moving the magnet towards the coil sets up the current, and if we supposed the magnet to be put on frictionless rollers, it

would seem that no energy is required to move it. Fig. 60 shows that this is not the case. Nature is as exact in her book-keeping of energy as a bank, and we cannot draw out more energy than we put in. When the magnet is approaching, a current is set up in the coil as shown by the arrow. This current makes the coil behave like a magnet, with its north pole towards the approaching north pole of the moving magnet. The coil therefore tends to *push the magnet away* as it

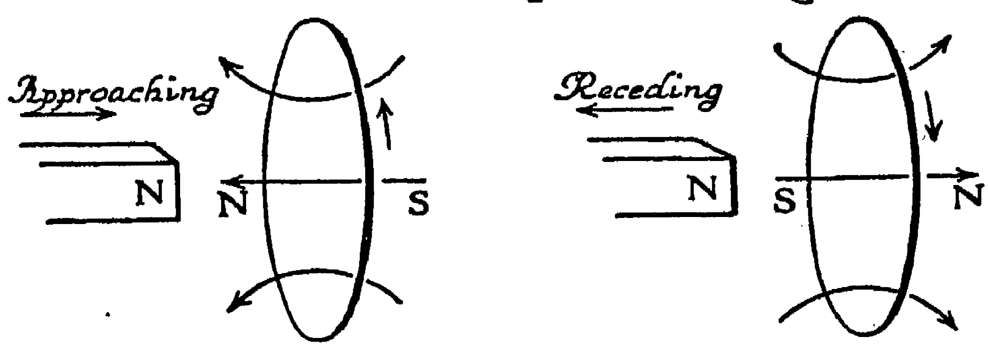


Fig. 60. An induced current runs in such a direction as to *resist* the movement which is producing it.

approaches and we have to do work against this force. When we draw the magnet away, the current runs in the opposite direction and therefore produces a magnetic field which tries to *hold the magnet back*, and we again have to do work to drag it away.

In the last experiment, a current is made by taking the N pole away from the coil. Perhaps you can see that a similar effect is produced if, instead of drawing the magnet away, we turn it round so that its S pole comes to where its N pole was previously (Fig. 61*a*). Finally, instead of turning the magnet round, we can turn the coil round (Fig. 61*b*); either movement produces a current in the same direction.

The effects shown in figures 58, 59, 60 and 61 are all different manifestations of the same principle. It is worth while studying them carefully, so that the idea

of electromagnetic induction may become completely familiar to us, because we will be constantly referring to it in this book.

This is the principle of the dynamo. If you go into a large power-station, you will see vast dynamos driven by steam turbines or other engines, and generating electrical current. These dynamos either rotate coils of wire between the poles of powerful magnets, or, more frequently nowadays, rotate powerful magnets

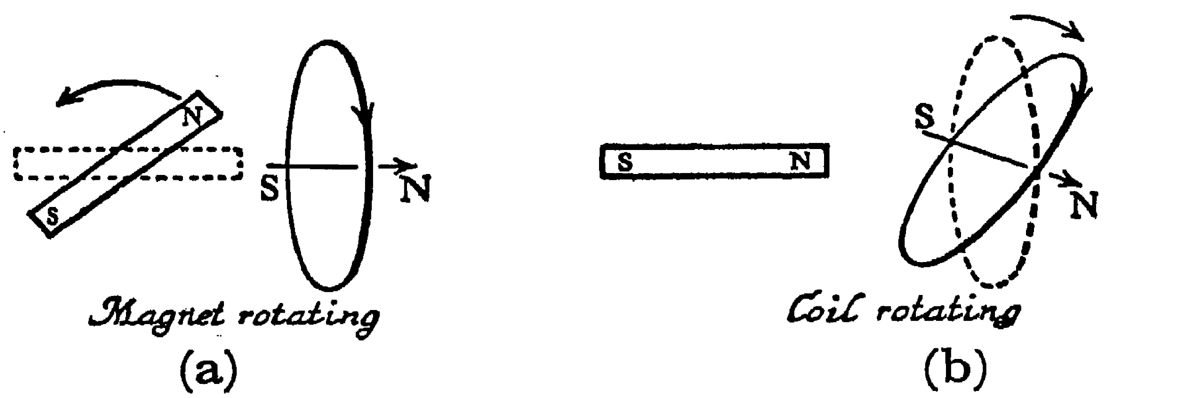


Fig. 61. Currents induced by the rotation of magnet or coil.

near coils of wire, and the impulses of current created in this way are sent into the mains.

We may use exactly the same model to show how a dynamo works as that which we used to show how a motor works. A motor and a dynamo are in fact quite alike except for technical details of construction. In the Christmas lectures I promised I would turn the motor we had already been experimenting with into a dynamo. We had a large label in front of it with MOTOR on one side and DYNAMO on the other, and when we came to talk about the dynamo we merely turned the label round. If the armature is driven by the handle (Fig. 55, Plate 12) a current is developed which lights the beacon on the right.

You will see that Fig. 62 looks very like Fig. 56.

In the motor, when a current is supplied to the armature, it spins round and can be made to do work. In the dynamo, on the other hand, the armature is spun round by an engine and gives out a current. An armature rotates between the poles of a powerful field magnet marked N and S in the illustration. If we look at (*a*) we will see that the pole marked A is just leaving the N pole of the field magnet, and the pole marked B is just leaving the S pole. The magnetic

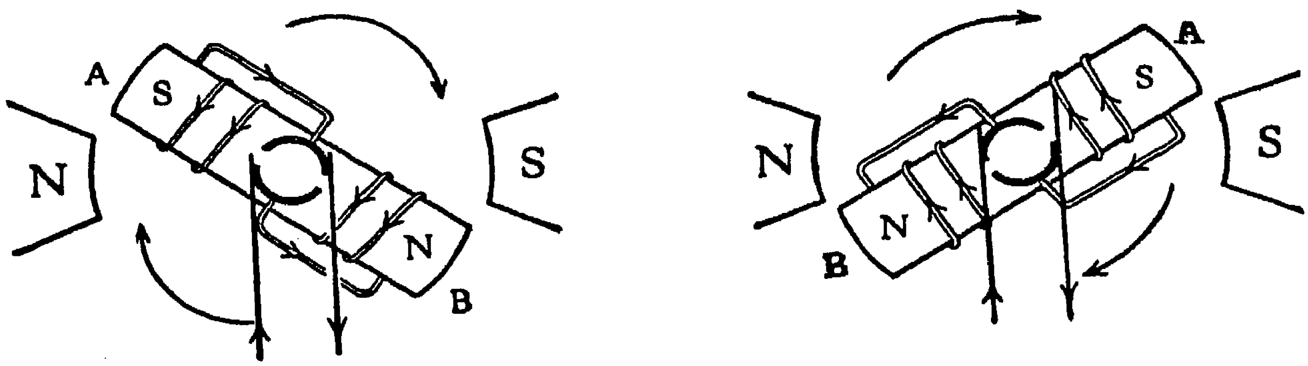


Fig. 62. The principle of the direct-current dynamo.

field inside the coils of the armature is changing, and a current is therefore induced in the armature winding. We can always find the direction of an induced current by remembering that it is like the most 'die-hard' of Conservatives. For instance, if a magnet is approaching a coil, a current runs so as to try to push the magnet away and keep things as they were, and when the magnet is leaving it tries to hold it back. 'No change' is its motto. Figures 60 and 61 illustrate this law. In the present case, the current in the armature runs so as to make the end marked A a south pole, and the end marked B a north pole. We may say that it is making an ill-natured attempt to stop our turning the armature. The direction is still the same in position (*b*), where A is approaching the S pole of the field magnet, and the current tends to make A a south pole

so as to push it away. Directly the ends of the armature pass the poles of the field magnet, however, the current alters direction. It is now trying to prevent the ends leaving the poles, just as previously it tried to prevent their approach. Here the commutator comes in, as in the case of the motor. The connections between the brushes and the armature windings are exchanged at this point, and although the current reverses its direction in the armature coil, it continues to be driven out by the right-hand brush and to return by the left, as the figure shows. When the armature is spun round rapidly an impulse of current is sent out in the same direction for every half-turn.

A dynamo of this simple kind, as in the case of the corresponding motor, would be very jerky in its action, giving a number of pulses of current one after the other. Actual dynamos have more complicated armatures, which are designed so as to give an even flow of current, though they work on just the same principle. The construction of such an armature is rather complicated to illustrate by a diagram, but Fig. 63, of an early form called the Gramme armature, suggests how a steady current is obtained. The armature is a ring of iron with an endless coil of wire wound round it. Connections lead from the loops of the coil to a number of commutator bars as shown.

To see how the current will run in such an armature, let us think how it must run in order to make us work as hard as possible when turning the armature round, for this principle always gives the right answer. We will suppose the armature is being turned in the direction of the arrow. Obviously, if the induced current makes the top of the ring a south pole and the bottom

a north pole, we will be working hard against the magnetic attractions and repulsions. Current therefore flows as shown by the arrows, moving up the coils on

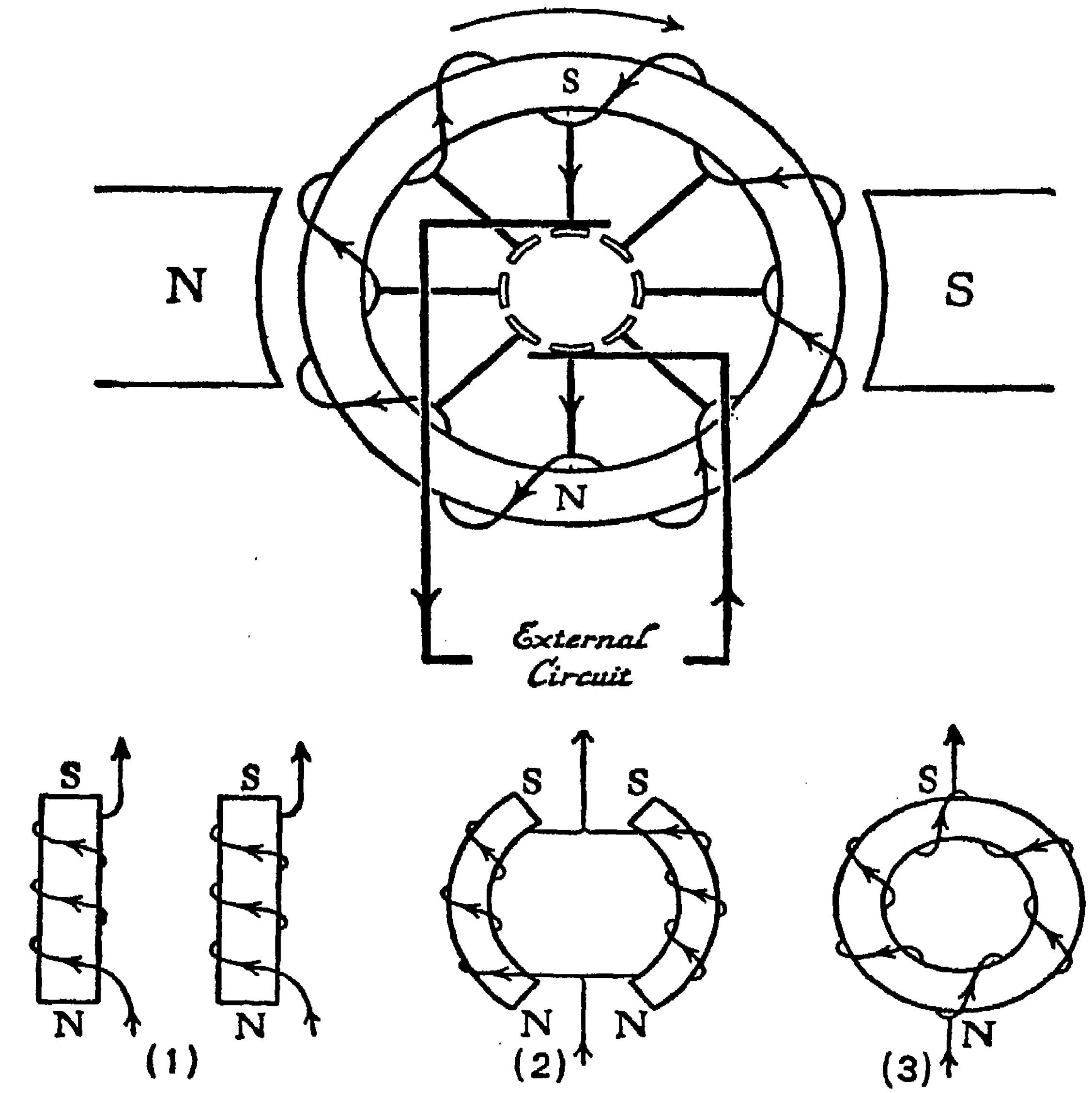


Fig. 63. The 'Gramme Ring' armature. The sketches at the bottom of the figure show how the currents in the armature produce a south pole at the highest point and a north pole at the lowest point of the ring.

both sides of the armature.[1] The currents from each side unite at the top to flow to the commutator bar which happens to be uppermost at that instant, where they are collected by one of the brushes. The current

[1] As it may be puzzling to see how the current makes the top of the ring S and the bottom N, I have put a series of little sketches in the figure to make it clear.

then flows round the external circuit and back by the lower brush to the bottom of the endless coil. It will be clear that such an arrangement gives a much steadier current. It is inefficient because the iron of the armature does not fit snugly between the pole pieces. We can get a much stronger magnetic field if the clearance is made small, and in actual motors and dynamos you will notice that the windings are placed in slots of the iron armature so that armature and poles nearly touch each other.

We have talked so far of what is happening in the armature of a dynamo and taken for granted the existence of a powerful field magnet. In the early days of dynamos, the field magnet was 'excited' by a separate battery. Then the brilliant idea was conceived of making the current from the armature excite the field magnet as well as feed the external circuit (see Fig. 68). Very little energy is required for the magnet, so that it does not reduce the output of the armature by much. The dynamo then becomes independent. When it is started up, there is always a little residual magnetism in the field magnet which starts a weak current in the armature. This current makes the field magnet stronger, which in turn produces more current in the armature, and so on till the dynamo is working at its full power.

7. BACK ELECTROMOTIVE FORCE

The effect described in this paragraph is one which many people find difficult to understand, though it ought to be quite obvious if we have got our electrical common-sense into good working order.

Suppose we take a small electric motor which is

adapted to work from direct-current mains. We connect it to the mains but prevent its armature from turning by gripping the axle. We shall find that an excessively large current passes through the motor, and if it is allowed to flow for any length of time the coils on the armature will probably get so hot that the insulation is burnt and the motor ruined. On the other hand, if the armature is allowed to turn freely, the current is quite small and the motor keeps cool.

The effect can be investigated in a better and less expensive way by putting an ammeter in the circuit, so that we can measure the current running through the motor. We shall find that when the current is switched on to a motor initially at rest, a very large current passes at first while the motor is getting up speed. When the motor is running light at full speed, i.e. not doing any work, the current falls to a low value. If we now make the motor do some work by causing it to drive machinery or by putting a brake on its axle, the current rises again, though not to so high a peak as when the motor is started.

To understand this effect you must remember that a motor and a dynamo are really one and the same thing. When the armature of the motor is starting up from rest, or when it is prevented from moving, the current which passes through the armature is only limited by its resistance. This resistance is purposely made as low as possible, because we do not want to waste energy in overcoming it, and therefore a very large current indeed passes through the armature. As the motor gets up speed, however, it begins to act like a dynamo, trying to drive current in the *reverse* direction to the current supplied by the mains.

This can be seen from Fig. 64. When working as a motor the current from the mains makes A north and B south so as to drive the armature in the direction of the arrow. Suppose we cut off the current from the mains to the armature, and consider the motor as now being a dynamo with the armature driven in the same direction. The induced current runs in such a way as to oppose the motion of the armature; it therefore makes A south and B north. The current in (*b*) is in the reverse direction to the current in (*a*).

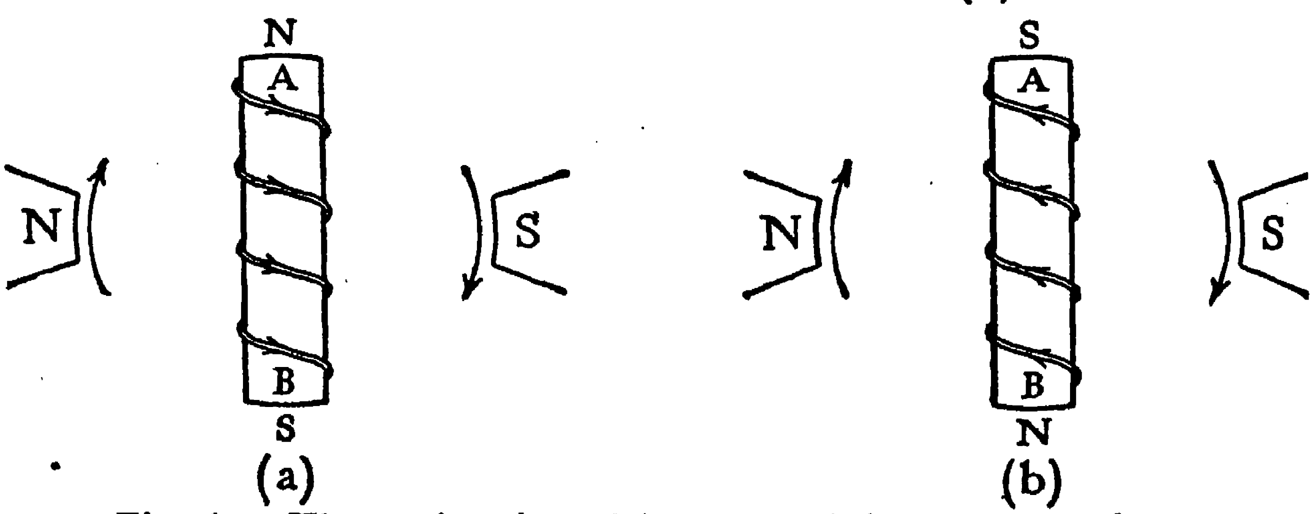


Fig. 64. The explanation of 'back E.M.F.' When running as a dynamo, the armature develops a current in the reverse direction to that of the current required to drive it as a motor.

Perhaps you can now see what happens when the motor is started up. At first the armature moves so slowly that there is practically no dynamo action. The current in it is only limited by its resistance and is very large. As the motor speeds up, the dynamo effect increases. If the motor is running light, its speed increases till the 'back electromotive force' due to the dynamo effect very nearly balances the electromotive force or voltage of the mains, and the current passing through the armature becomes small. It never drops quite to zero, because some energy is required to overcome friction; the mains must always just win in the

fight. When the motor has to do work, the armature is slowed down. The 'back E.M.F' drops, more current flows, and this extra current represents the supply of energy from the mains which does the work.

Figs. 65 and 66 (Plate 14) illustrate an experiment which we showed at the Christmas lectures. In Fig. 65 a motor is being driven from the main supply, which can be switched on by S_1. A lamp L is lit by the current from the mains when the switch S_2 is closed. Three ammeters A, B, C enable us to read the current supplied by the mains, the current running through the motor, and the current running through the lamp. The ammeters, which Messrs. Weston kindly made especially for us, had a central zero, so that currents in one direction moved the needle to the left and in the opposite direction to the right. In the actual experiment the motor had a fly wheel on its axle so as to increase its inertia, which exaggerated the usual effects and made them easier to observe. Starting with the motor at rest, when the switch S_1 is closed the motor takes a large current which swings the needles of A and B to the ends of their scales on the left (about 1·5 amperes). As the motor gets up speed, the needles creep back, and when it is going full speed the current is only a fraction of an ampere. When the lamp is turned on by S_2, C registers the small current taken by the lamp and A the sum of the currents taken by motor and lamp. We now open the switch S_1, thus cutting off the main supply. *The lamp continues to burn almost as brightly as before.* We can see where the current is coming from by watching B, whose needle jumps to the *right* directly the mains are switched off. The motor, which keeps rotating owing to its inertia, has become

a dynamo driving current through in B the *opposite* direction to that supplied by the mains, and so feeding it in the same direction into the lamp. By watching

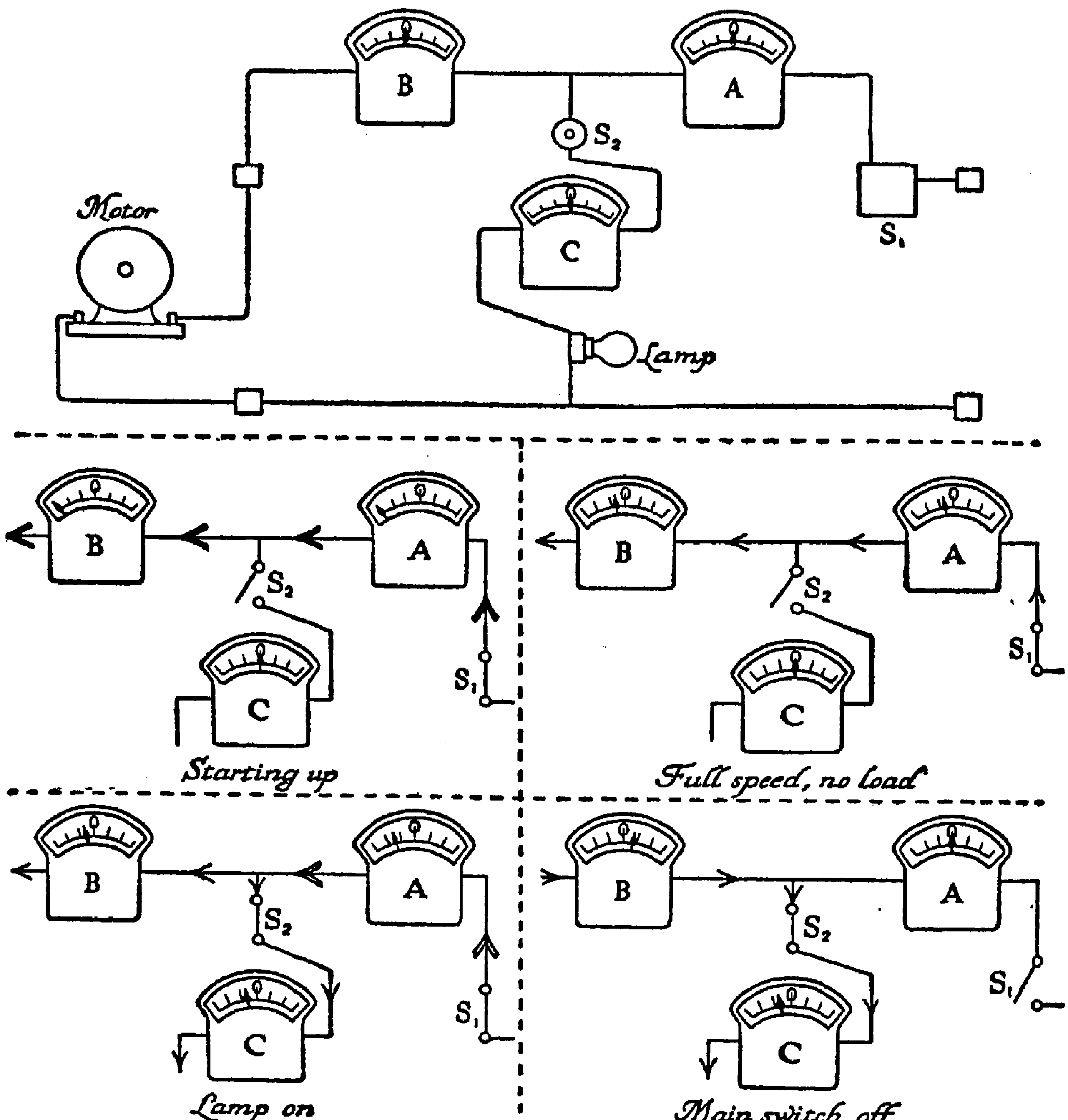


Fig. 65. An experiment to illustrate 'back E.M.F.'

C we can see that this current in the lamp is nearly as great as the current which it previously took from the mains; this shows that the back E.M.F. developed by the spinning motor is very nearly equal to the voltage

of the mains and explains why the motor takes so little current when at full speed. When the motor is lighting the lamp it is doing work and therefore slows down, and the current gradually dies away.

Fig. 66 (Plate 14) is a photograph of the apparatus used to demonstrate the effect. The motor can be made to do work by putting a brake on it by means of the handle you see on its left. When the brake is put on, the motor slows down and the current rises. A clutch is also provided by which the motor can be made to raise a weight by a crane. When pulling up the weight it takes more current. The motor is very handy because it adapts itself to the work it has to do. We might think that current is being wasted when a motor in a workshop is left running all day although the lathes, drills and milling machines are only used intermittently, but the waste is very small. When running 'light' the motor conveniently cuts down the current to a mere trickle by its back E.M.F. Directly it is faced with a job of work it allows more current to pass. It is like a motor-car which presses its own accelerator when it comes to a hill. The characteristic noise of a small motor such as those used to work the clippers in a barber's shop shows the effect very well. When switched on they accelerate rapidly with a rising note till they give out the steady hum characteristic of the 'no load' speed. When clipping operations commence the note drops, and rises again to its steady value each time clipping ceases It is worth while thinking over the effects I have just described rather carefully, for they teach one a great deal about motors and dynamos.

A large motor takes a long time to get up speed

owing to its inertia. If the full voltage of the mains were switched on when at rest, so large a current would pass that it might be damaged, or the current would blow the fuses or actuate the safety cut-out which breaks the circuit. The motor is therefore provided with a starting 'rheostat'[1] (Fig. 67). When starting up the handle is moved to the first stud. The current has to flow through a large resistance and is prevented from becoming too great. As the motor picks up speed, more and more resistance is cut out by moving the handle to the right. On the right-hand side you will see a little electromagnet excited by the current from the mains which grips the handle in position when all the resistance is cut out. This is called the 'no-volts release.' If by chance the current from the mains were cut off with the motor running, and the handle remained over to the right after the motor stopped, then when the current was switched on again the motor would get the full force of it and there would be trouble. The no-volts release magnet provides for this emergency by letting the handle go when the main supply is cut off, and the handle is pulled back to the starting position by a spring. The other little electromagnet at the bottom left-hand corner is the safety cut-out or overload release. The main current passes through this magnet and if it becomes too large the magnet pulls out a switch, so that a careless person trying to start the motor too quickly is prevented from doing damage. You may have noticed in electric trams that sometimes when one is starting there is a

[1] A rheostat is a resistance which can be varied by altering the amount of resistance wire in the circuit, generally effected by means of a sliding contact.

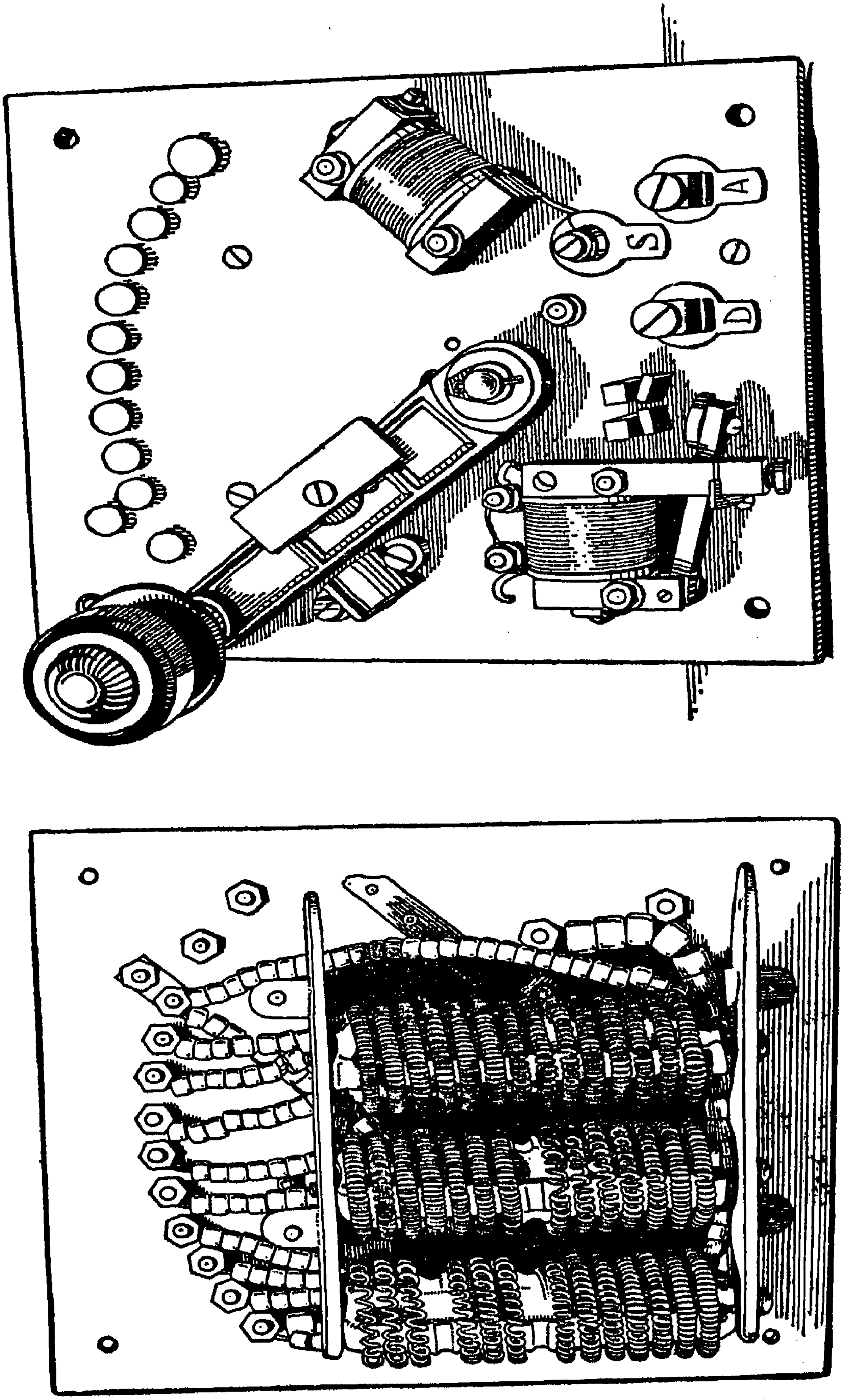


Fig. 67. A starting rheostat, with safety cut-out and no-volts release.

tremendous bang and flash in a box on the rear platform, and the tram cannot move till the guard has pushed home a switch which has been tripped in this way. The driver has been in too much of a hurry to start, and, instead of using his starting resistance properly, he has thrown an excessive current into his motors. He is warned by the safety cut-out to be more considerate in applying the load.

8. SHUNT AND SERIES EXCITATION

There are two ways of connecting the circuits in the armature and field magnet of a motor or dynamo, known as 'shunt' and 'series,' which are shown in Fig. 68.

In a series-wound machine the whole of the current through the armature passes also through the field magnet. In a shunt-wound machine, armature and field magnet are separately connected across the mains. To take motors first, the field magnet of a shunt-wound machine has always the same strength, whatever current the armature is taking, because the full voltage of the mains is applied to it. A motor of this kind behaves as I have just described, running at a constant speed when there is no load and dropping its speed slightly when it has to do work. It is the convenient kind of motor for workshops. A series-wound machine behaves quite differently. If we apply a voltage to the motor when at rest, the very large current going through the armature also goes through the field magnet, making it excessively strong, and the combination of strongly excited armature and field magnet gives the motor a tremendous power when starting up. Such motors are used for electric trains and trams,

which have to start quickly. On the other hand, we cannot allow such a motor to have no work to do, because it cannot prevent itself going faster and faster till it bursts ! If you think it out, you will see why this is so. The armature tries to go so fast that its back E.M.F. nearly stops any current going through it. But the more successful it is in stopping the current, the weaker does its field magnet become, and therefore

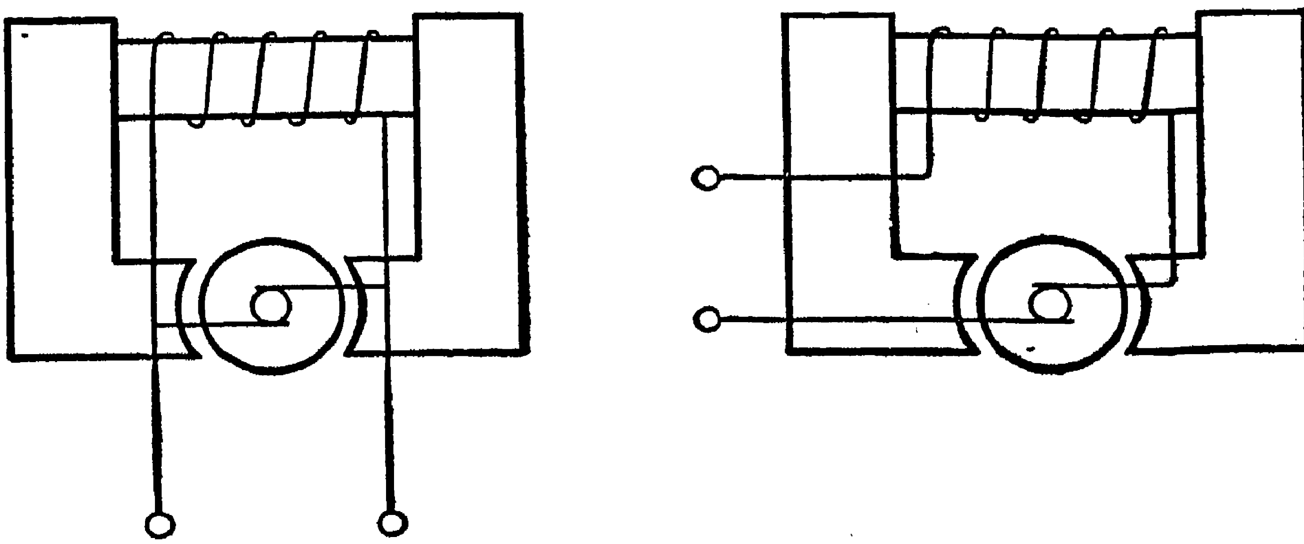


Fig. 68. A 'shunt wound' (left) and 'series wound' (right) motor or dynamo.

the faster it has to go again to build up the back E.M.F. Series-wound motors are only safe when they are geared to the driving wheels of a train so that they cannot go too fast.

Dynamos are shunt-wound for obvious reasons. We want them to supply a constant voltage, whether current is being drawn from them or not, and so we must keep their field magnets fully excited. If a dynamo were series-wound, the field magnet would hardly be excited at all when it is supplying a small current, and so the voltage would drop off. If a shunt-wound dynamo is being asked to give a heavy current, however, the voltage tends to drop a little, and so it is

usual to have a few 'series turns' on the field magnet, as well as the 'shunt turns,' so as to boost it up when a heavy current is being taken and keep up the voltage.

9. SUMMARY

It has been my experience that students find the idea of electromagnetic induction harder to grasp than any other in electricity and magnetism. I think this is partly because it is not so easy to make simple experiments which show it. The forces between charges and between magnets are easily tested. Everyone is familiar with the little electromagnets in electric bells, and becomes reconciled to the idea that in some mysterious way a current running round a piece of iron makes it a magnet. On the other hand, it requires rather delicate apparatus to show the current which is induced by moving a magnet near a conductor or vice versa, though nowadays one can get delightful toy dynamos which light a pea lamp when they are spun round, and the sparks from the magneto of a car engine are convincing evidence of the reality of the effect. We must become thoroughly familiar with it. We must remember that the effect of the moving magnet is to produce an electromotive force which tries to make a current run. Whether the current actually runs or not depends on whether it finds a conducting path. Finally we must remember that the current will run in such a direction that we are forced to do work to produce it. This law, known as Lenz's law, is only natural, because we cannot expect to get a current for nothing. If you will remember these clues, I think you will find them excellent guides.

PLATE 14

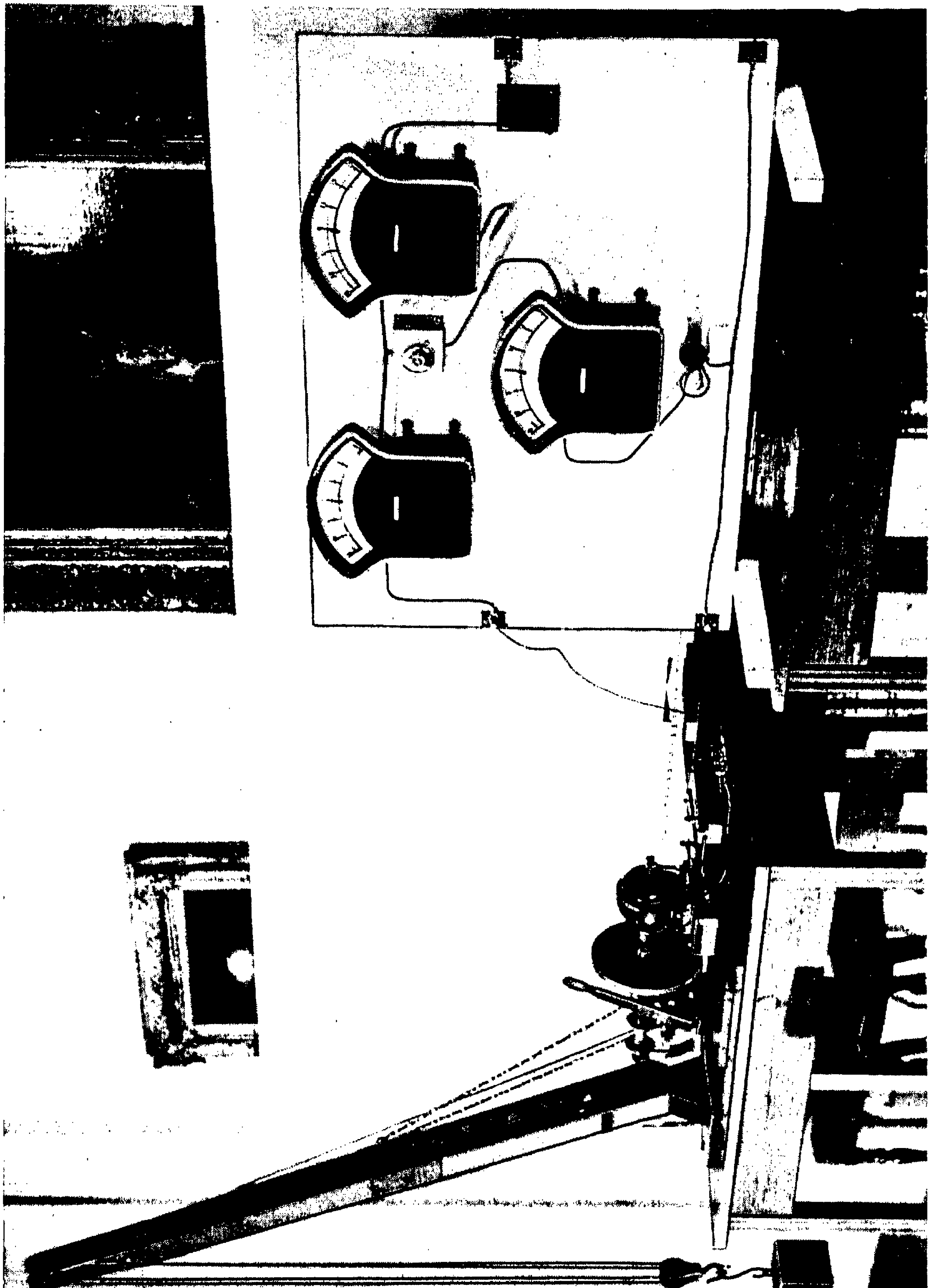


Fig. 66. An experiment to illustrate 'back electromotive force'

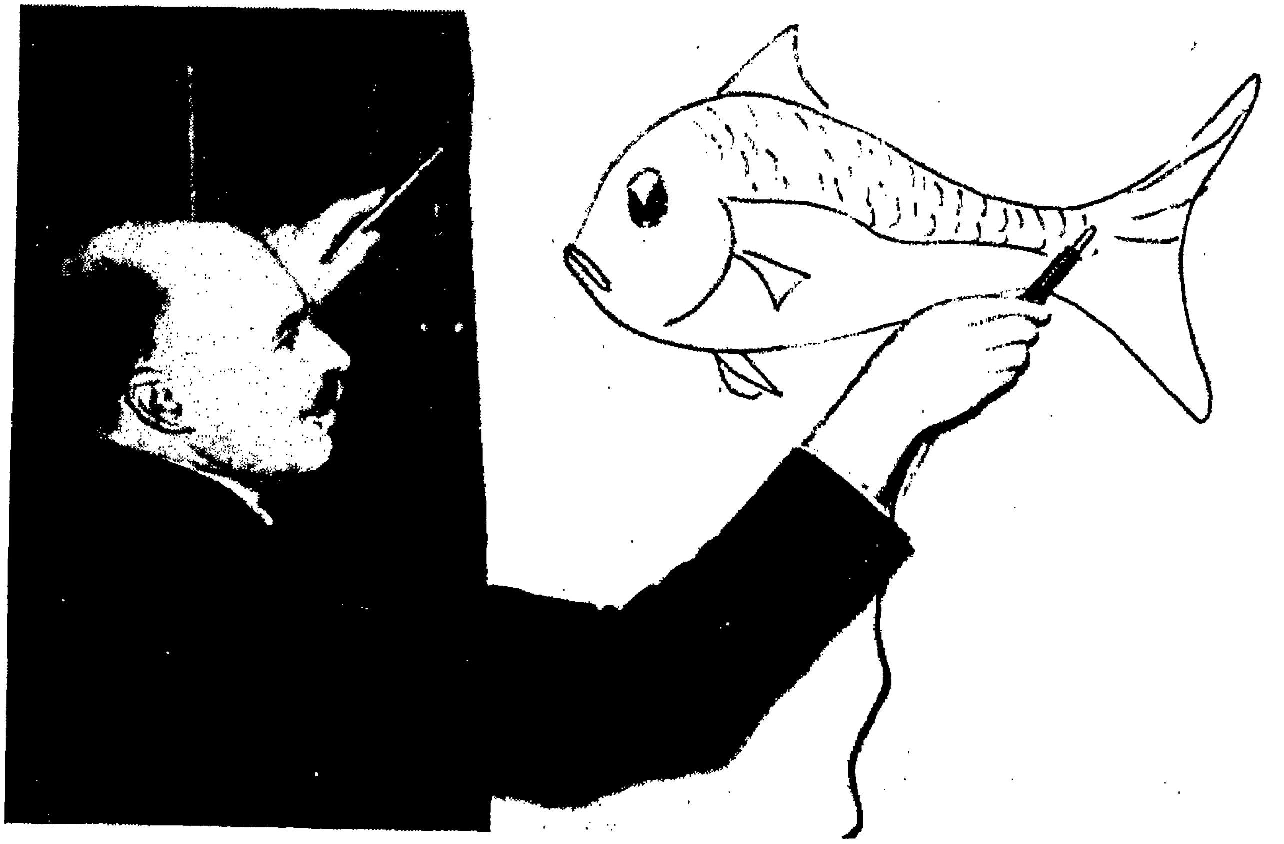


Fig. 69. Drawing with a positive electrode on a sheet moistened with starch paste and potassium iodide. (*'Sphere' photograph*)

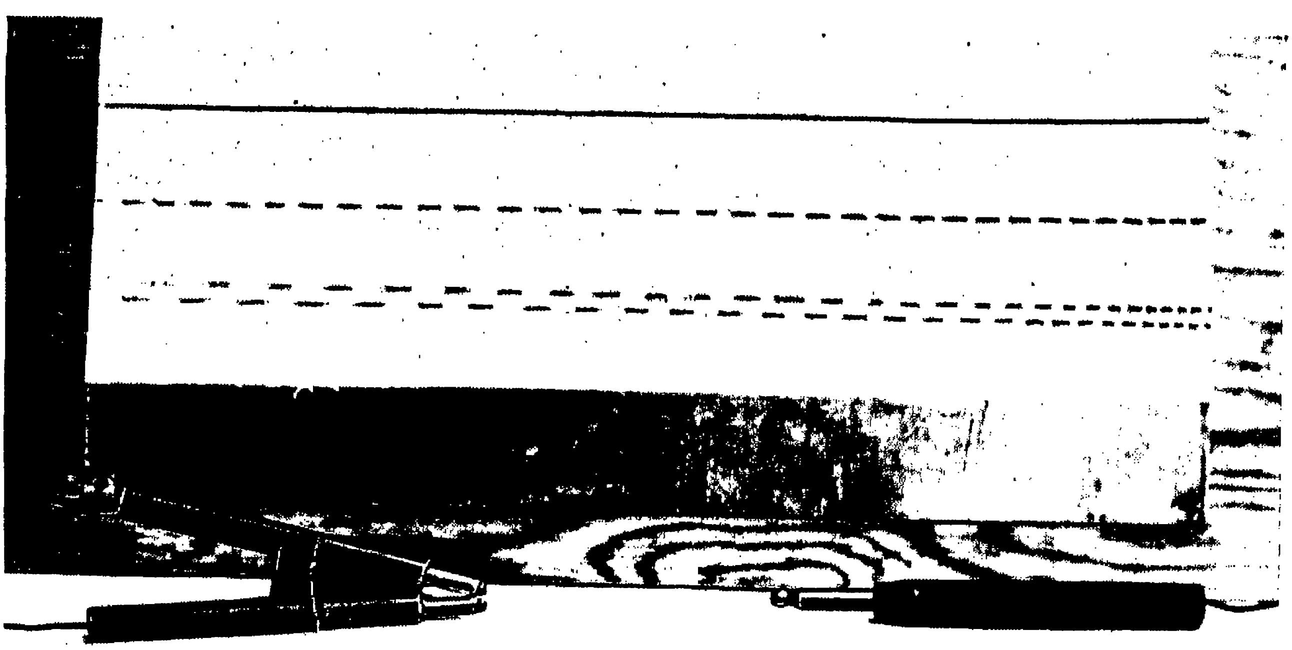


Fig. 70. The upper line is drawn with a positive electrode (direct current). The next line is drawn with one lead from an alternating current supply. The lower pair of lines are drawn with the two leads from an A.C. supply. Note the alternate spacing of the marks. The track was drawn in about half a second

CHAPTER IV

OUR ELECTRICAL SUPPLY

In the first three chapters we have been studying the principles of electricity and magnetism, becoming familiar with the behaviour of charges, currents, and magnetic fields. The remaining chapters deal with the practical application of these principles to three great divisions of electrical engineering. In the first place there is the generation transmission and use of electrical power, which comes under the heading of heavy-current electrical engineering. Then there is the use of the electrical current to convey messages from one place to another, by telephone, telegraph or submarine cable. The currents employed are very small, and our concern is not with the development of power but with delicate and complicated variations in the electrical current. Just as paint may be used either to cover the Forth Bridge or a canvas in the Royal Academy, so the electrical current may be used to convey either gross power or a message from one human brain to another. This latter is light-current electrical engineering. The final chapter describes some properties of high-frequency currents. It would form a natural introduction to the study of wireless telegraphy and telephony, but that subject is so vast that it could not be dealt with comprehensively here and I must be content with a description of the principles of the oscillating electrical circuits on which wireless is based.

The present chapter deals with the generation and transmission of electrical power on a large scale.

I. THE FUNCTION OF A SYSTEM OF ELECTRICAL SUPPLY

A system of electrical supply is not a new source of power, it is merely a new way of conveying power from one place to another.

Previous to the industrial development which began about 150 years ago, most of the power which was required for various human activities was developed in the muscles of men or of animals. Men worked the land themselves, or used horses or oxen to draw the plough. Transport was by horse-drawn carriages or pack horses in the more advanced communities and by human porters in more primitive ones. In earlier times much heavy work was done by gangs of slaves, who could be fed on the cheapest of food and whose bodies turned that food into available power. The typical exceptions to the almost universal use of muscle were such simple operations as could be carried out monotonously and in a leisurely way at a fixed point such as grinding corn or pumping water. Windmills and water-wheels were used for grinding corn because they could be placed at convenient sites on hills or in valleys, and the corn could be brought to them. Windmills were used for pumping water in flat countries like Holland and our fen district in Norfolk. They were only required to keep down the general water level in the ditches and had no sudden emergencies to cope with. A spell of calm weather when the windmills could not work was compensated for by a succeeding windy spell.

The development of the steam engine marked an

immense change, for it became possible to have a steady supply of power at any place to which fuel could be brought. As one can observe in Lancashire, the earliest factories had to be placed in valleys where water power was available. With the advent of steam power, they could be placed anywhere so long as coal could be brought cheaply to that place, and it was for this reason that the big industrial areas in England grew up around the coal-mines. Even in these days of railways, it is still an expensive business to convey coal for long distances, as is shown by the difference in price of coal in different parts of the country.

The development of the generation and transmission of energy in electrical form marks another immense step forward in control over power. It must be emphasized again, however, that this is not because a new source of power is available, but because a new way has been found of sending power from the places where it is conveniently developed to the places where it is needed. I may perhaps take an analogy from the way power is distributed in a large workshop or mill. A central engine drives a system of overhead shafts with pulleys, from which belts descend to many machines. It would be highly wasteful and inconvenient to have a small engine to drive each machine, and this difficulty is overcome by transmitting power through the shaft and belt drive. We must compare a system of electrical supply to the system of shafts and pulleys; for it is essentially a method of transmission. It is still necessary to have a source of power or 'prime mover' such as a steam engine. This engine drives a dynamo in a power station which converts mechanical power into electrical power. The current flows out

from the station along the mains and is used to drive motors at the places where mechanical power is needed, or to provide us with light and heat. It is a marvellous method of transmission because it is so simple and efficient. Instead of a clumsy system of belts and pulleys or of cog-wheels which can only transmit the power a few yards and even then waste a good deal of it, we can convey many thousand horse-power along slender wires. I believe it was Oliver Wendell Holmes who called it power stripped stark naked. The power can be sent hundreds of miles by transmission lines, and then run by cables to any part of a building where it is required. There is a story of a Lancashire manufacturer which illustrates its possibilities very well. An electrical engineer was trying to persuade him to convert his factory from the belt drive with which he had grown up into an electrical system, and explained that if the machines were driven by motors they could be arranged in a more convenient way than if they all had to be aligned so as to be driven by overhead shafts. At last the manufacturer grasped the point and said to the engineer: 'Do you mean to tell me that this electricity can go round a corner?'

You can understand, then, what a revolution the widespread distribution of electrical power is bringing about. Instead of having to build an engine at any place where power is required, we only have to link that place to the main electrical supply by overhead wires or underground cables, the power being developed wherever it is most convenient. Factories need no longer be grouped around the coal areas nor need each factory have its chimney belching forth smoke.

A big generating station can afford to instal the plant necessary to cope with the smoke from its furnaces, cleaning it and removing the harmful gases. By centralizing the development of power in power stations, it is also possible to develop it more cheaply, because much more energy is got from each pound of coal by large engines than by small ones. Electricity is one of the greatest assets in curing the ugliness, dirt and lack of planning which have spoilt so much of the country and are bad legacies from the last century.

2. ELECTRICAL UNITS

I have tried to avoid definitions and formulae in this book as in the lectures, but since we are now discussing practical electrical engineering we must have some idea of the units used to measure electrical quantities, just as we have to know roughly what is meant by 'second,' 'hour,' 'foot,' 'mile,' 'pound,' and 'ton,' in the ordinary practical affairs of life when we are ordering the coal or reckoning how long a motor journey will take.

A good way of acquiring a familiarity with electrical units is to quote figures for some examples with which most people are familiar.

The *ampere* is the unit of *rate* of flow of current.

The current flowing through an ordinary 40-watt lamp on the 230-volt mains is about $\frac{1}{6}$ ampere. An electric radiator uses from 10–20 amperes and it is therefore necessary to use much stouter leads for wiring up a radiator than those which are required for a lamp. The self-starter of a motor-car requires as much as 100 amperes for the few seconds it is in action, and frequent attempts to start a cold engine soon run the battery down. The minute currents which convey our

voices along telephone wires are of the order of one ten thousandth of an ampere.

The *Volt* is the unit of potential, or as it is sometimes expressed, of 'electromotive force' (E.M.F.). You will remember that if we compare an electric current to the flow of water, we may say we measure the rate of flow in amperes and the pressure or 'head' in volts.

A dry cell has an E.M.F. of 1·5 volts, and an accumulator cell of just over 2 volts. A motor-car battery generally consists of six accumulator cells in series, giving a total of 12 volts. The standard voltage for house supply in this country is 230 volts, though as the current supply is of the 'alternating' type, to be described below, this figure requires further definition. Alternating current is generated in power stations at various voltages, but 6,600 volts, 11,000 volts and 33,000 volts are common. The 'Grid' (see page 181) operates at 132,000 volts. Potential differences in a thunderstorm rise to one thousand million volts.

The *Watt* is the unit for measuring power, or the rate at which electrical energy is being used or generated.

To obtain the number of watts, we multiply volts by amperes.[1] The volts measure the pressure which is driving the current, and the amperes the rate at which current is flowing, so clearly they must be multiplied if we are to get a measure representing the power. Lamps are marked with the number of watts they consume, 25, 40, or 60 watt lamps being common ratings for household use. When a measure of larger

[1] It is again necessary to qualify this statement in the case of alternating current, where a relation called the 'power factor' has to be considered.

amounts of power is required, the kilowatt is convenient. A kilowatt is one thousand watts, and corresponds to $1\frac{1}{3}$ horse-power.

The *Coulomb* is a measure of electric charge, being the amount which would pass any point in a circuit each second if an ampere were flowing. We have previously mentioned 'electrostatic units of charge'; the coulomb is a more convenient unit when dealing with currents. An accumulator cell delivers during discharge a total number of coulombs which depends on the size of its plates. Since this number is inconveniently large, we generally reckon the capacity of the cell in 'ampere-hours' and not coulombs which are 'ampere-seconds.' A small cell in a wireless set may have a capacity of 25 ampere-hours, and a cell in a motor-car of 100 ampere-hours.

The 'unit' which appears in the quarterly electricity bills represents the supply of one kilowatt for an hour or its equivalent. An electric radiator consumes two or three kilowatts, say four horse-power. It brings home very clearly the cheapness of electrical power, if we think that when an electric fire is turned on we have the equivalent of several horses working for us, and that it only costs a few pence to hire them for an hour. A big power station like Battersea will yield 480,000 kilowatts when fully developed, and work continuously as hard as more than half a million horses. If we allow a reasonable working day to the horses, we might reckon that it would take two million to provide us with the equivalent amount of power.

The *Ohm* is the unit of resistance. Everyone who has ventured at all into the study of electricity is familiar with Ohm's Law, which states that the current

passing through a conductor is proportional to the electromotive force driving it. The ohm is so chosen that $C=E/R$ where C is measured in amperes, E in volts, and R in ohms. Ohm's Law is almost unique in Physics, because it really is true! In the case of most 'laws' we have to make many qualifications and corrections, but within the accuracy of measurement Ohm's Law may be relied upon.

The intensity of the shock when a discharge passes through our bodies depends on the magnitude of the current. The shock when the 230-volt mains are touched gives one a sharp prick, but it is often harmless because the skin when dry has a high resistance and this voltage is unable to drive a dangerous current through it. It is a very different matter when the skin is wet so that a really good connection is made. A shock from the 230-volt mains may then be very nasty or even fatal. One must be particularly careful not to have faulty switches, or exposed leads to apparatus such as an ultra-violet equipment, in a bathroom, where they may be touched by damp hands. A higher voltage than about 500 begins to be dangerous in any event.

3. ALTERNATING CURRENT

When one is buying electrical equipment, one is generally asked whether the local supply is 'direct current' (D.C.) or 'alternating current' (A.C.). Most generating stations in this country are now being connected up with the grid, and the supply for ordinary domestic use is being converted into a standard one of '230 volt 50 cycle A.C.' We must see what this means.

A direct current flows steadily in one direction, like

the water in a stream; an alternating current flows backwards and forwards like the tides in an estuary. The mains which pass into our houses from a direct current supply (D.C.) have got a constant difference of potential between them. The potential of one may be, for instance, always 200 volts higher than that of the other, so that if we connect a lamp across the mains there is a steady pressure of 200 volts driving current through the lamp. The mains from an alternating current supply (A.C.) on the other hand have a fluctuating potential difference between them. First the one, then the other, is at the higher potential, and a current drawn from them flows alternately in either direction. If the current goes forwards fifty times and backwards fifty times in a second, we say that the supply has a *frequency of 50 cycles*, a cycle being a general name for one of a series of repeating events.

The nature of an alternating current supply can be illustrated by an artistic experiment, which we showed at the Christmas lectures, using a well-known effect to indicate the direction of the current. When a current runs through a solution of potassium iodide, it liberates iodine at the anode (see Fig. 33) by electrolysis, and ordinary starch paste turns a violet-black colour when it reacts with small traces of free iodine. A large linen cloth is soaked in starch paste in which potassium iodide has been dissolved, and it is then spread while still damp on a sheet of tinned iron. (It is worth remembering if this experiment is being repeated that a zinc sheet is not suitable, because the zinc stains the cloth dark brown in a very short time by chemical action.) If now we take two metal rods, provided with insulating handles and connected to a

D.C. supply of a few volts, and let the negative rod touch the metal sheet, a beautiful violet line can be drawn on the sheet with the positive rod because the iodine liberated by the current reacts with the starch. Fig. 69 (Plate 15) shows the author drawing a fish in this way. I strongly recommend this method of drawing to lightning artists, because an intensely dark and very uniform line follows the moving terminal, and can be produced at any speed with the lightest possible touch. If we exchange the terminals, only a faint smudge appears. The plate then becomes the anode and the terminal we are drawing with becomes the cathode. The iodine is liberated behind the sheet where it touches the plate, not in front of it, and the stain is only faintly seen through the sheet.

Fig. 70 (Plate 15) shows the effect of drawing rods attached to an alternating current supply across the sheet. In doing this experiment, the 230 volt A.C. supply may be used, provided one puts an electric lamp in each lead and care is taken to hold the rods by their insulating handles. If the lamps are there, an accidental contact between the rods only lights them, whereas if the leads are connected directly to the mains, the contact would make a 'dead short' and blow the fuses. The two rods are held side by side by their insulating handles, and drawn rapidly across the sheet. As you will see, each rod draws a dotted line, showing that it is alternately anode and cathode. Since when one is cathode the other is anode and vice versa, the dots are spaced alternately.

We now set a metronome to beat seconds, and after a little practice draw a pair of lines which start and stop at successive ticks of the metronome. The lines

should be two or three feet long. We will find that there are about fifty dots on each line; there would be just fifty if it were possible to draw for exactly one second. This demonstrates the 50 cycle frequency of the alternating current.

One can get fine artistic effects by drawing with one rod (the other lead being connected to the metal sheet), and asking an assistant to switch on direct current or alternating current as the picture needs continuous or dotted lines. The only drawback is that these works of art are not permanent, for they fade in an hour or so.

An alternating current successively has a maximum in one direction, falls to zero, has a maximum in the opposite direction, and falls to zero again. Its average value is clearly less than its maximum value. By 'an alternating current of one ampere' we mean a current which has a maximum value of 1·41 amperes ($\sqrt{2}$ amperes) each way, one ampere being what is called its 'root mean square' value. The same holds for an alternating voltage. In a '230 volt A.C.' supply, the potential difference actually oscillates between $\pm$ 325 volts.

An alternating supply of the kind we have been considering, which comes to us along two mains, is called a 'single-phase' supply. One of the cables coming into our houses is called the 'neutral' and is at zero potential. The other, the 'live' cable, has a potential oscillating between +325 volts and −325 volts as explained above. Although two wires run to each lamp, it is only necessary to have one lamp switch, connected to the 'live' main, because when the switch is off both wires become neutral and can be

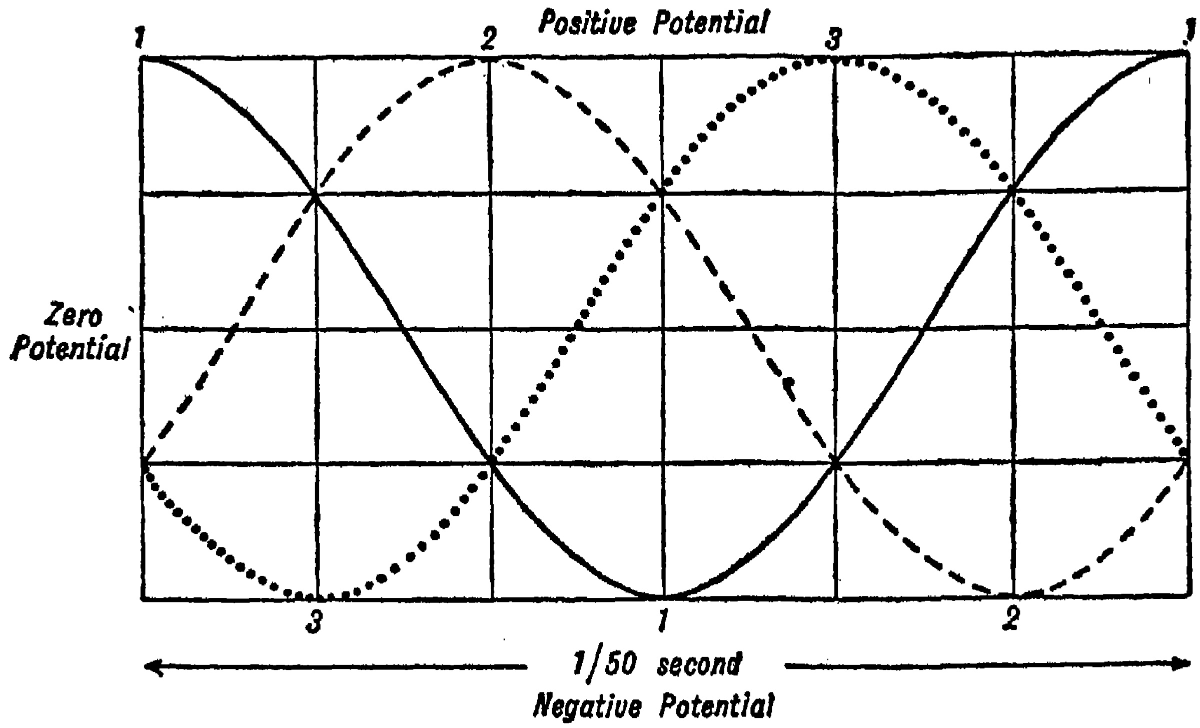


Fig. 71*a*. A three-phase supply. The potentials of the three wires are represented by the three curves.

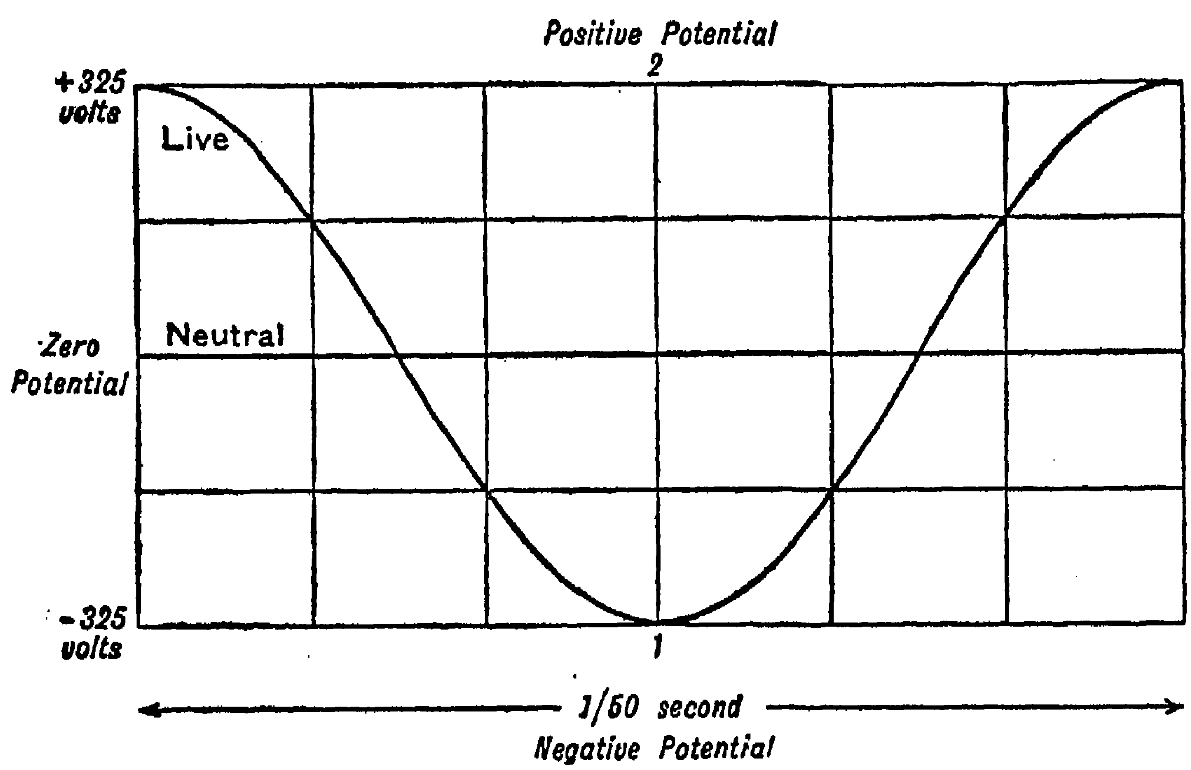


Fig. 71*b*. A single-phase supply. The curve represents the potential of one wire, the other 'neutral' wire being at zero potential.

touched without getting a shock. On the other hand, if you look at the lines which take the grid current across country (see Fig. 96, Plate 27) you will notice *three* lines on insulators. (The fourth slender line linking the tops of the towers is not carrying current, it is merely an earthing line which connects them electrically.) These conductors are conveying 'three-phase' or 'polyphase' current. If we call them 1, 2, 3, the lines reach their maximum positive potential in the order 1—2—3—1—2—3 fifty times a second. When 1 is at its maximum positive potential, 2 and 3 are negative and so on. Fig. 71 shows the potential changes of single-phase and three-phase supplies. Three-phase current is used for power transmission because it has certain technical advantages which will be described later, but the domestic supply is always single-phase.

4. WHY ALTERNATING CURRENT IS USED; TRANSFORMERS

What is the point of using alternating current? At first sight it seems a very odd thing to do. The cables going out from power stations are conveying alternating current. No sooner has the current started running in one direction than back it comes again. It is just as if the driving belts in a factory were going backwards and forwards instead of running steadily in one direction.

To understand this, we must first consider the problem of transmitting electrical power from the generating station to the place where it is to be used. The cables which convey the current have a certain resistance, which is the greater the longer the distance the current has to be taken. Some of the power is wasted in driving the current through the cables against the

resistance. The resistance is made as low as possible by using wires of copper or aluminium which have a high conductivity, and by making the cables thick. However, the weight of the cables cannot be increased beyond a certain point, for they then become very costly and too heavy to be carried as overhead lines by towers or poles. We must therefore avoid wasting power in the lines by keeping the current along them as small as possible, since the rate at which energy is lost in useless warming of the wires depends only on the resistance and the current. On the other hand, since vast amounts of power must be conveyed from one place to another, if the current is to be small the voltage must be very high, for you will remember that power is measured by multiplying current by voltage.

This is the sole reason for using high voltages on transmission lines. You cannot fail to have noticed the long strings of insulators on the towers, and the notices at the foot of each tower, 'Danger, 132,000 volts.'

Let us imagine we had to send the same electrical energy from one part of the country to another at 230 volts direct current, instead of 132,000 volts alternating current, with no more waste due to resistance than at present. Currents would be nearly 600 times as great, and the cables would have to be 35 feet across instead of $\frac{3}{4}$ inch as they actually are. You can see what an enormous advantage is gained by transmitting at the high voltage.

The energy is therefore sent out from generating stations at high voltages, in order to keep the transmission losses small. On the other hand, it must be

tamed down to a small voltage before it can be used. The 230 volts of the domestic supply is practically the highest possible voltage which is safe in a house.

Alternating current is used because it is so easy to change from one voltage to another. In order to turn a *direct current* at one voltage into a direct current at another voltage, the first current must be used to drive a motor, which drives a dynamo so designed as to give the different voltage. This is a relatively expensive equipment and needs constant attention. It is also difficult to design motors and dynamos for very high voltages, because the insulation of the coils becomes a serious problem. An *alternating current*, on the other hand, can be converted from one voltage to another in a very simple way by a *Transformer*.

You may remember the story of the man who was shown a giraffe for the first time, and said, 'I don't believe it's true!' Of all the electrical apparatus, I think the transformer makes one most inclined to say the same thing when one first appreciates what it does. It seems almost incredible that anything so simple should be able to hand on energy in such a convenient way.

A transformer consists of two coils of wire wrapped around the same piece of iron. One coil is called the primary and the other the secondary. If an alternating current is fed into the primary, an alternating E.M.F. is set up in the secondary in which a current will run if the circuit is complete. Fig. 72 (Plate 16) shows the transformer in a very simple form. The primary is a coil wound round an iron bar, which projects for some distance beyond the coil. The secondary is a separate coil of wire, with its ends joined up through a lamp. If

now we pass A.C. through the primary, and lower the separate coil over the iron rod, we shall find that the lamp lights up, faintly at first and more brilliantly as the secondary approaches the primary coil. You will notice that we are handing on a current from the one coil to the other without contact of any kind between the two.

The principle by which the transformer works is simply the principle of electromagnetic induction which we have already studied. The alternating current in the primary makes the iron rod an electromagnet with its North pole alternately at either end. Each time the magnetization of the iron rod is reversed, an electromotive force is induced in the secondary. We therefore get an alternating E.M.F. in the secondary which can be used to drive a current with the same frequency as that of the primary current.

If this were all, nothing would seem to have been gained, since we have merely got a current like that with which we started. However, let us suppose that we make a transformer with a few turns of thick wire in the primary, and a large number of thin turns in the secondary. By passing a *large current at low voltage* into the primary, we are able to draw a *small current at high voltage* from the secondary. This will work backwards, for it does not matter which coil is called the primary and which the secondary. By passing a small current at high voltage into the coil with many turns, a large current at low voltage can be drawn from the coil with few turns.

This latter effect is shown by the experiment of Fig. 73. An iron ring is wound with a large number of turns and connected to the A.C. mains. A very thick

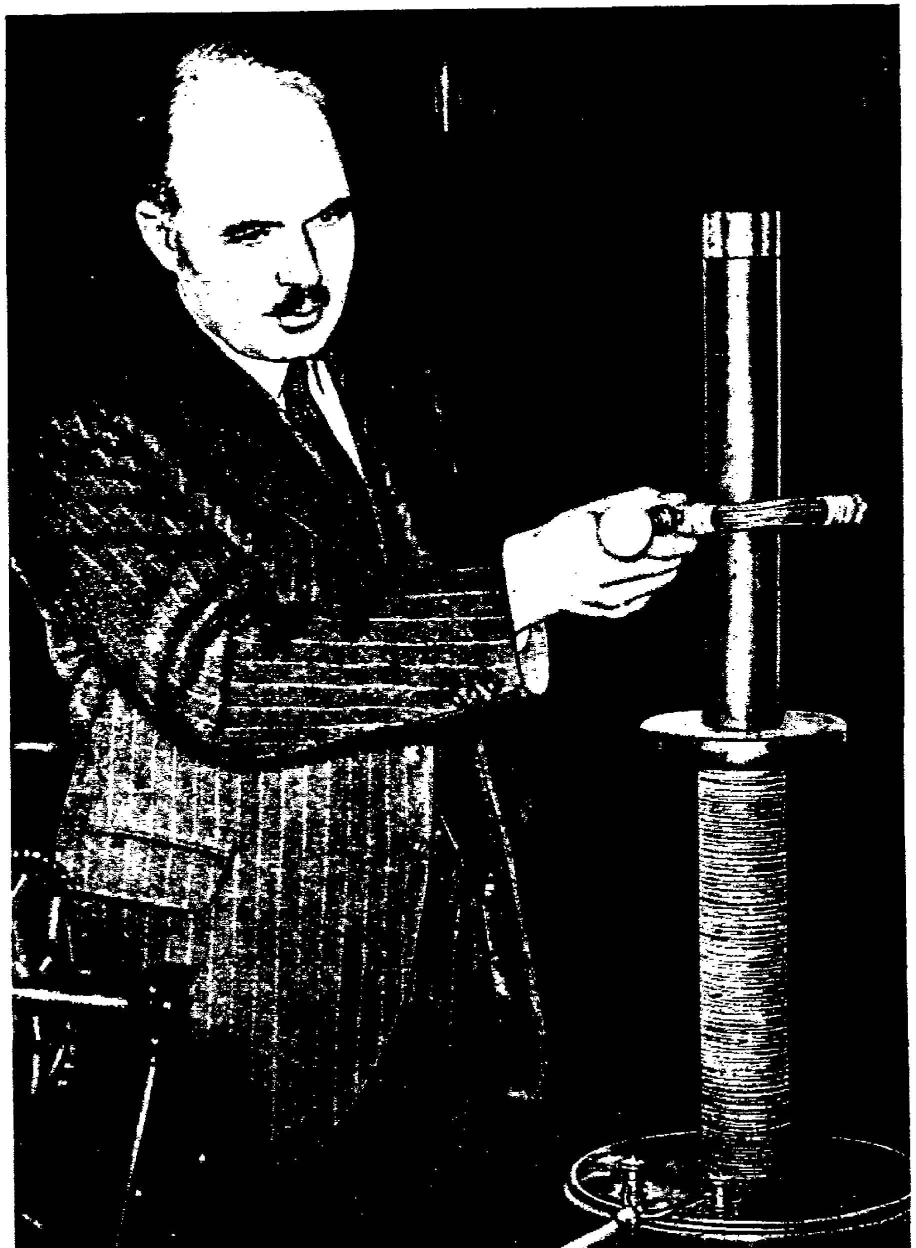


Fig. 72. The action of the transformer. The lamp is lit by currents induced in the coil connected to it, when an alternating current passes in the lower coil. ('*Sphere*' *photograph*)

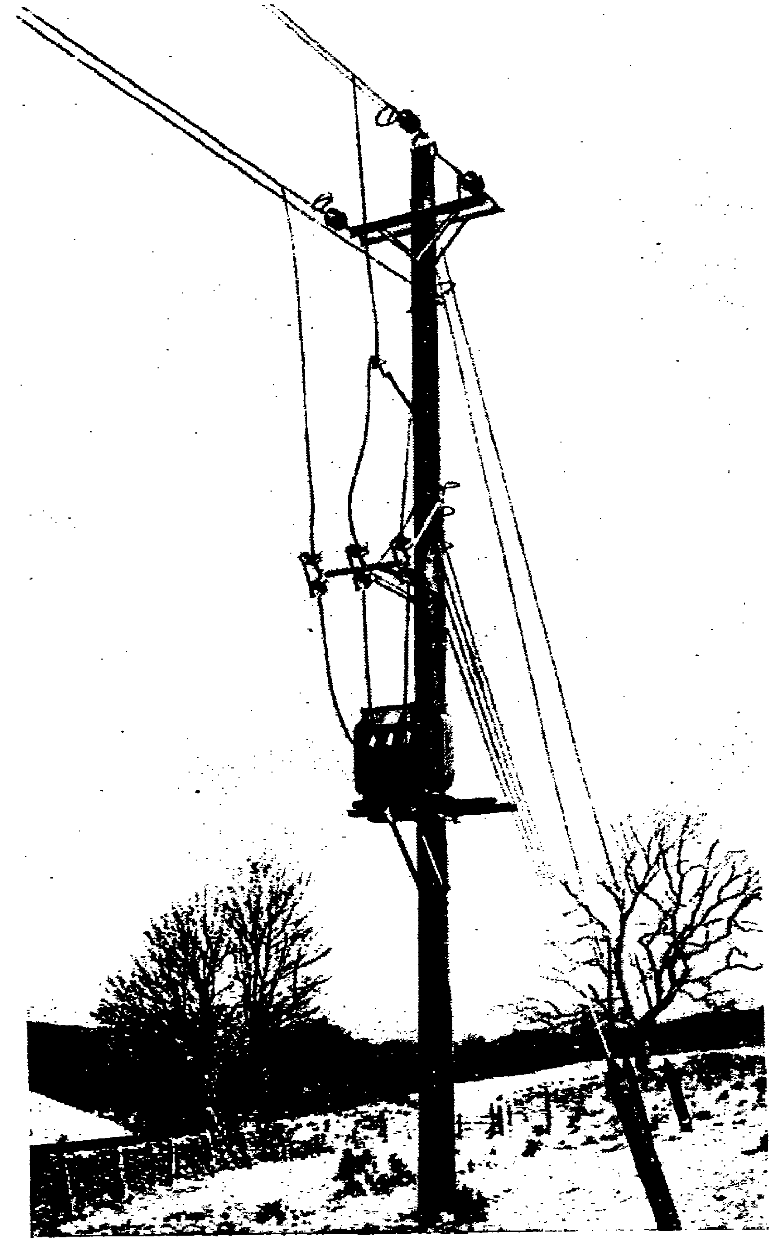


Fig. 75. A transformer mounted on a pole. (*Central Electricity Board*)

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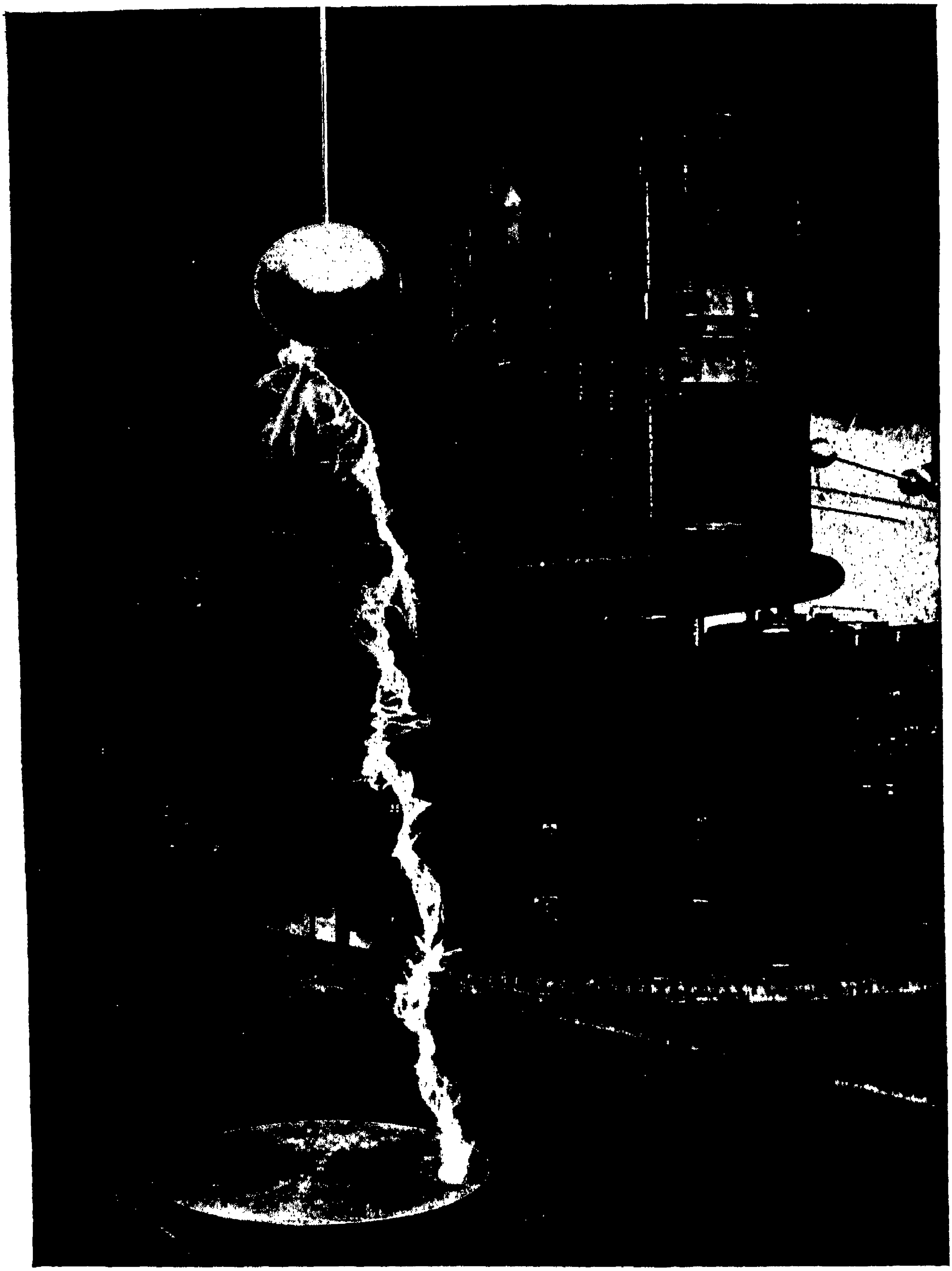


Fig. 74. A million-volt transformer. (*Metropolitan-Vickers*)

copper wire is coiled two or three times around the ring as shown in the figure, and its ends are clamped to an iron nail. Putting quite a moderate current into the primary, so large a current flows in the secondary that the nail soon gets white hot and melts.

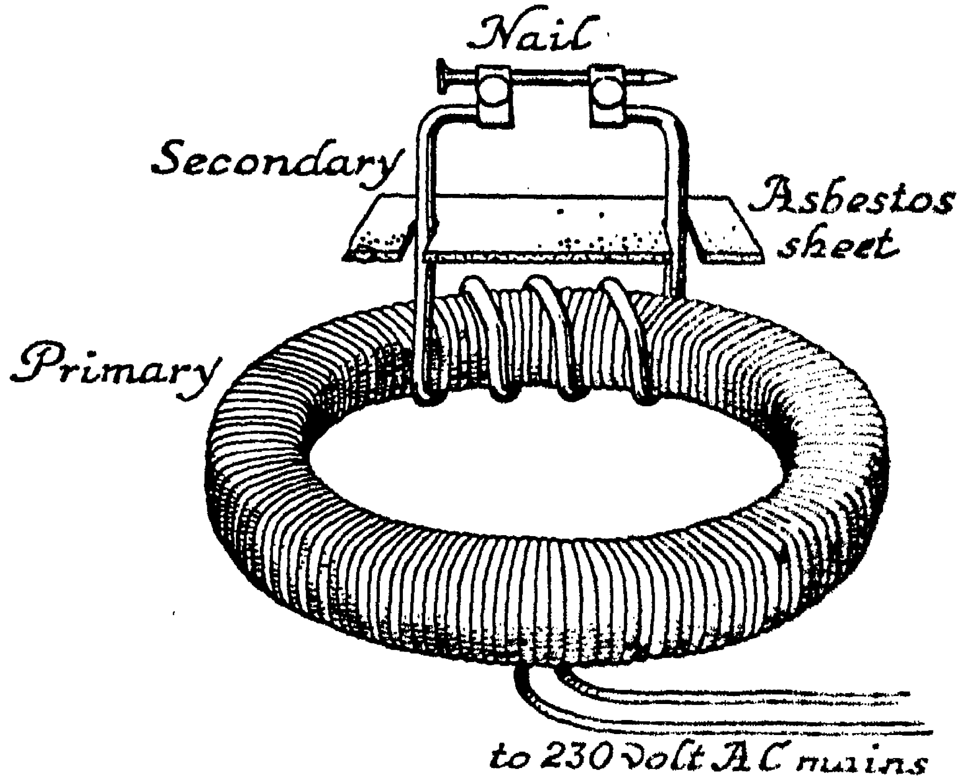


Fig. 73. Melting a nail with a 'step-down' transformer. The asbestos sheet protects the transformer from the molten metal.

Fig. 74 (Plate 17) shows the opposite effect in a gigantic 'high tension transformer' used in the research laboratories of Metropolitan-Vickers to test insulators. The potential between one end of the secondary winding and earth rises to one million volts, and produces the discharge seen in the foreground.

It is easy to see that as we increase the number of turns of wire in the secondary of a transformer, we increase the voltage. The magnetic changes produced by the primary induce a certain voltage in each turn of the secondary, and these voltages all add together. The rule for the increase or decrease is a simple one.

If there are N times as many turns on the secondary as on the primary, the voltage goes up N times.[1]

A transformer thus gets its name because it is able to transform a supply of power represented by alternating current at a certain voltage into a supply at a higher or lower voltage. If used to raise the voltage it is called a 'step-up' transformer, if to lower the voltage it is called a 'step-down' transformer. It is so useful because it is relatively cheap to construct and has no moving parts. It does not need to be started up, and requires no attention when running. You may have noticed the iron huts, often to be seen near small towns or villages, with high voltage wires running to them. They contain transformers, converting the current from a high voltage to the low voltage which is supplied to the neighbouring houses, and they are only visited at intervals for a routine inspection.

Fig. 75 (Plate 16) shows a little step-down transformer mounted in a pole. The high tension supply at 11,000 volts is coming from the left and is led down to the transformer. One can see the low tension cables (230 volts) running away in the distance to supply local needs.

Fig. 76 (Plate 18) shows a large transformer used for converting three-phase alternating current[2] from a power station from 33,000 to 132,000 volts. This transformer can convert 30,000 kilowatts. The photograph was taken before the transformer was put in its

[1] We may emphasize here a point which is dealt with more fully below. Although we may get an increased voltage from the secondary, we cannot use it to produce an unlimited current, since we cannot get more energy from the secondary than is supplied to the primary. In other words what we gain in voltage we lose in current.

[2] It is actually three transformers in one, since the current is three-phase.

PLATE 18

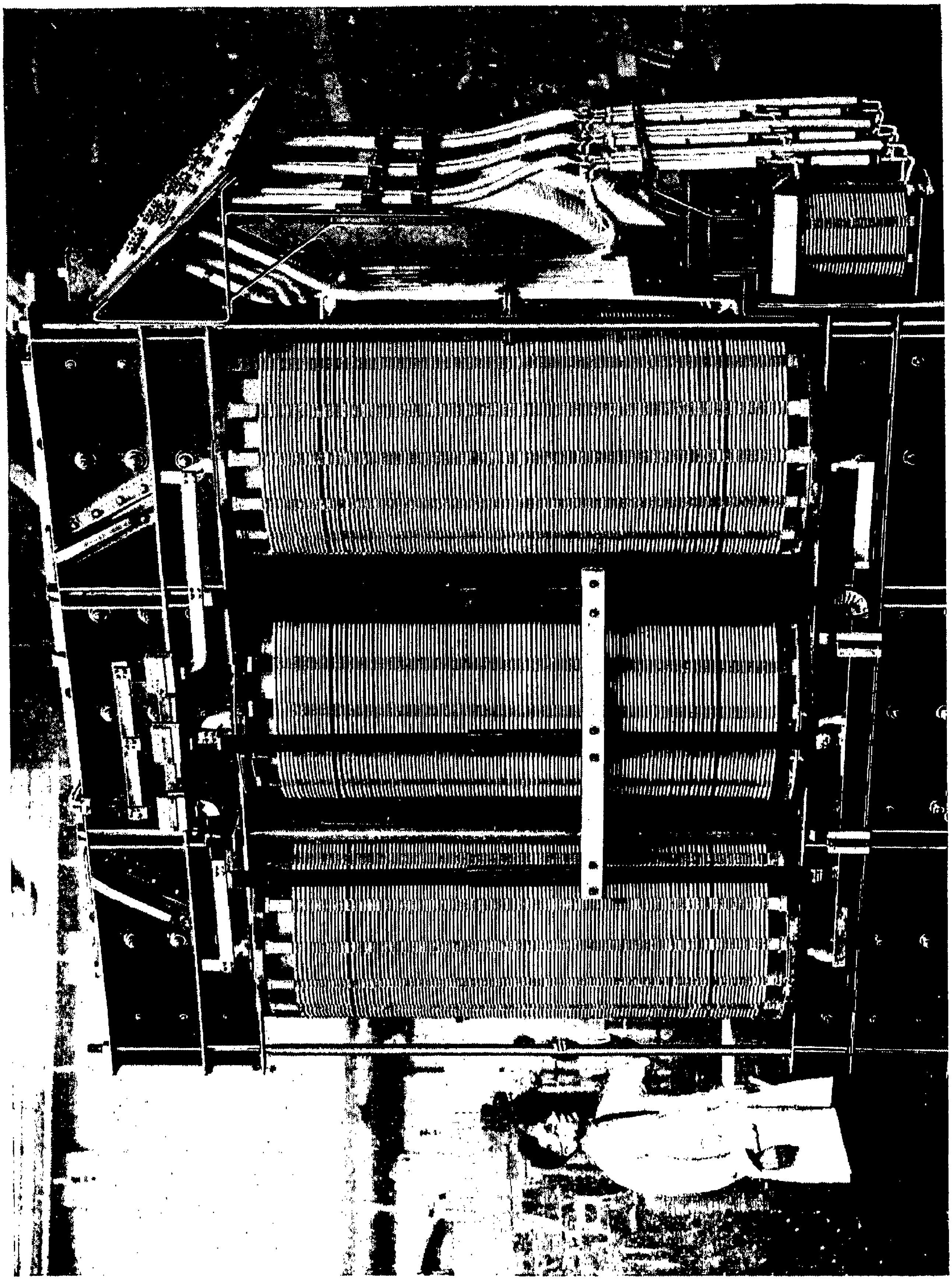


Fig. 76. A 30,000 kilowatt transformer for three-phase current, removed from its tank (*Metropolitan-Vickers*)

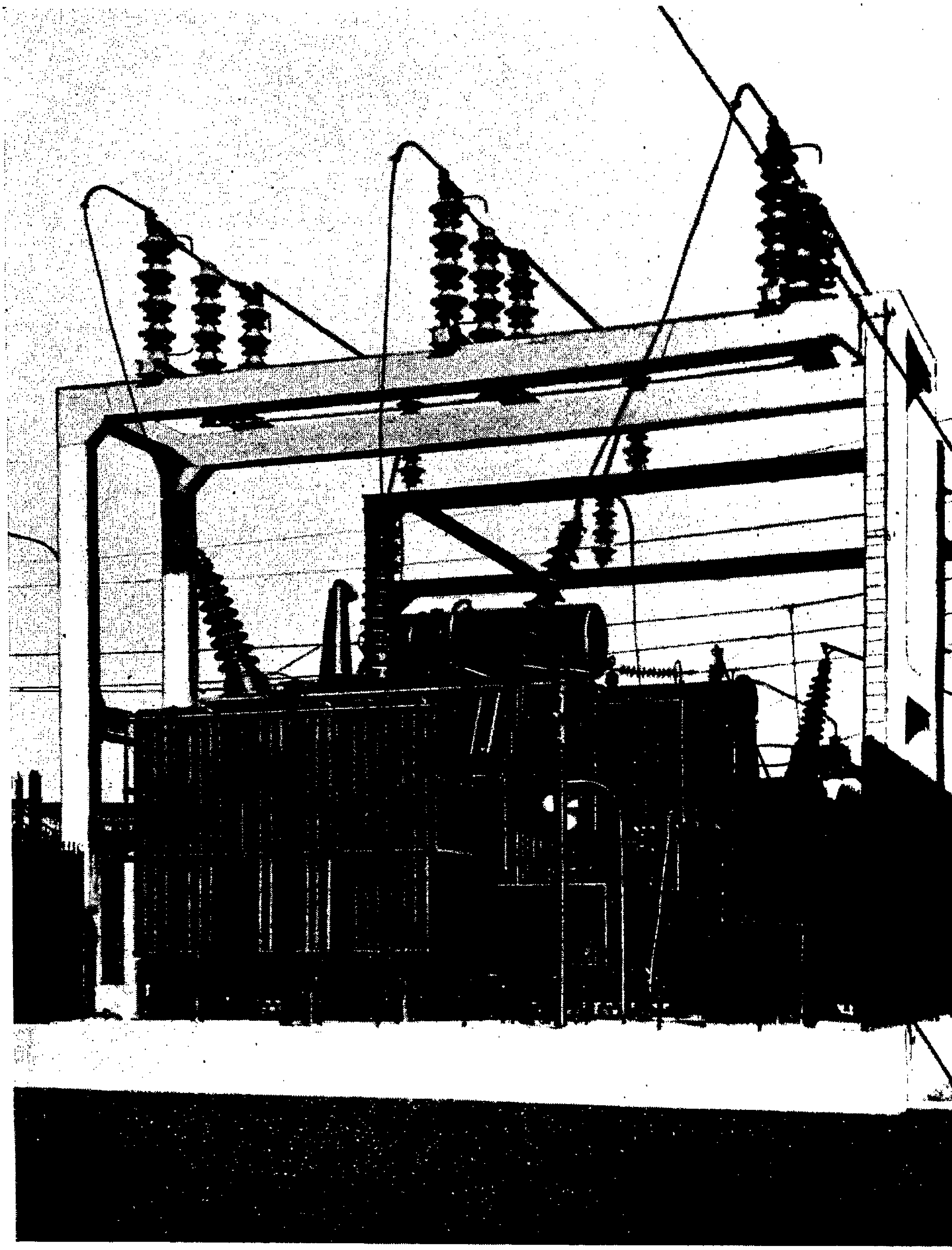


Fig. 77. A transformer in an outdoor substation. Note its cooling radiator in the foreground (*Metropolitan-Vickers*)

case; when actually working it is placed in a large tank holding about 7,000 gallons of oil which serves a double purpose. It is a better insulator than air, preventing discharges between the coils at the high voltages for which the transformer is designed. The oil also cools the windings and the iron core, just as the cylinders of a motor-car are cooled by a water jacket. The transformer has big 'radiators' on either side also like car radiators, where the oil in turn is cooled by the air. You will see in the figure gaps in the windings of the transformer so that the cooling oil can flow all round them.

Fig. 77 (Plate 19) shows a 15,000 kilowatt transformer installed in an outdoor sub-station, with its radiator nearest to us in the picture. This transformer is 'stepping down' from 132,000 to 6,600 volts.

A transformer is very efficient, converting practically all the energy which is put into the primary into energy which is given out by the secondary. In a well-designed transformer the loss is only about 2 per cent.

At this point I can imagine a reader with an enquiring mind (and I am sure anyone who has struggled thus far in my book has got an enquiring mind) saying 'Stop! This is very hard to believe. The voltage of the mains is driving a current through the primary coil of the transformer. The secondary coil is not connected to it in any way whatever. How can it matter at all to the current in the primary what the secondary is doing? To put it in a way which makes it seem most absurd, let us suppose the secondary is cut off from the lamps or motors to which it is giving its energy, so that no current is running in it at all. Surely all the current in the primary is just running to waste.'

This question cannot be answered properly without doing quite a complicated bit of mathematics; engineers, who are not over-fond of mathematical equations, sometimes use a graphical method to solve such a problem, i.e. they get the right answer by drawing a diagram. Though it would be out of place to plunge into mathematics here, I am anxious that the reader who has asked a perfectly natural question should have a hint as to the answer.

Suppose in the first place that the secondary circuit is broken at some point, and consider what happens when an alternating voltage tries to drive an alternating current through the primary. At a certain moment, let us say, the voltage is zero, but is mounting up in a direction we will call the positive direction. It starts a current in the primary coil which magnetizes the iron core. Induction now comes into the picture. Because the field inside the coil is increasing, there is a 'back E.M.F.' trying to oppose the increase and so pushing against the voltage. If the voltage keeps on trying to drive the current in the same direction, it will win in the end as it does, for instance, when we make a battery drive a current through an electromagnet. In the present case, however, before the voltage has time to build up a large current, it reverses and tries to drive a current in the opposite direction. Again an induced E.M.F. comes into play and opposes the change, for you will remember the rule that induced E.M.F.s always try to prevent any alteration in a magnetic field. As a consequence, the current through the primary coil is very small, far less than it would be if we applied a corresponding constant voltage to it. We say that the primary coil 'chokes' the alternating current.

When the secondary is connected to a circuit and is giving out energy, a much larger current flows in the primary. It is hard to explain why this is so without the formulae, but perhaps you will see in a general way what is happening. With an 'open'[1] secondary, the current in the primary is choked because it cannot create and reverse the magnetic field fast enough. It is like an engine trying to shunt a heavy train backwards and forwards fifty times a second. On the other hand, if a secondary current is able to flow it runs one way when the primary current runs the other way, and they partly cancel each other's magnetic effects. This is what actually happens when the secondary circuit is closed. The primary current is no longer choked to the same extent by its attempts to make and destroy magnetic fields rapidly, because the induced secondary current keeps the fields smaller by always flowing the opposite way. The primary current begins to do more work, and that is where the energy supplied by the secondary comes from.

Here are some figures from the specification of a big transformer, to make things seem more real. The transformer converts 30,000 kilowatts from 132,000 to 6,600 volts or vice versa. When it is idle, the 'magnetizing current' in the primary is only 2·9 amperes, whereas when on full load the current is 131 amperes.

Most of the magnetizing current of an idle transformer, small as it is, does not represent waste of energy. The voltage mounts up and starts a current in the primary. When the voltage dies away to zero, this current goes on running, kept up by the induced E.M.F.

[1] An 'open' circuit is one which is broken at some point so that current cannot flow round it.

It continues to run even when the voltage is reversed, and while it is doing this it *feeds back energy into the mains*, just as a dynamo would. You can imagine it saying to the voltage, 'You've got me started; I'm hanged if I'm going to change just to please you.' In every alternation, the current runs for nearly half the time *against* the voltage, giving back nearly all the energy it gets. The idle transformer therefore absorbs very little energy indeed from the supply to which it is connected.

Currents which are running out of sympathy with the alternating voltage in this way are called 'Wattless amperes.' They do not represent useful energy. When we really want the current to do something, the part of it which is wattless is a nuisance because it only warms up the wires without doing any work. When an engineer says that his 'power factor' is high, he means that most of his amperes are really doing work and not being wattless, or, to put it more precisely, that current and voltage are very nearly in step with each other.

Even if my reader finds this difficult to follow it has perhaps been worth while to hint at these effects if only to show that alternating current behaves in a very different way to direct current, and that we must revise our ideas when we come to deal with it.

5. EDDY CURRENTS; ALTERNATING CURRENT SUPPLY METERS

Meters deserve a section to themselves. I mentioned an alternating current meter at the beginning of the book as an illustration of the difficulty of understanding how electrical machinery works. It really is difficult to understand, even when one has some

knowledge of electricity and magnetism. If the reader follows the working of the meter, he may congratulate himself on having got the idea of induction clearly.

We must start off with the idea of *eddy currents*. When a magnet approaches or recedes from a coil of conducting wire, a current is set up in the wire by electromagnetic induction.

Suppose there are two coils of wire A and B, and

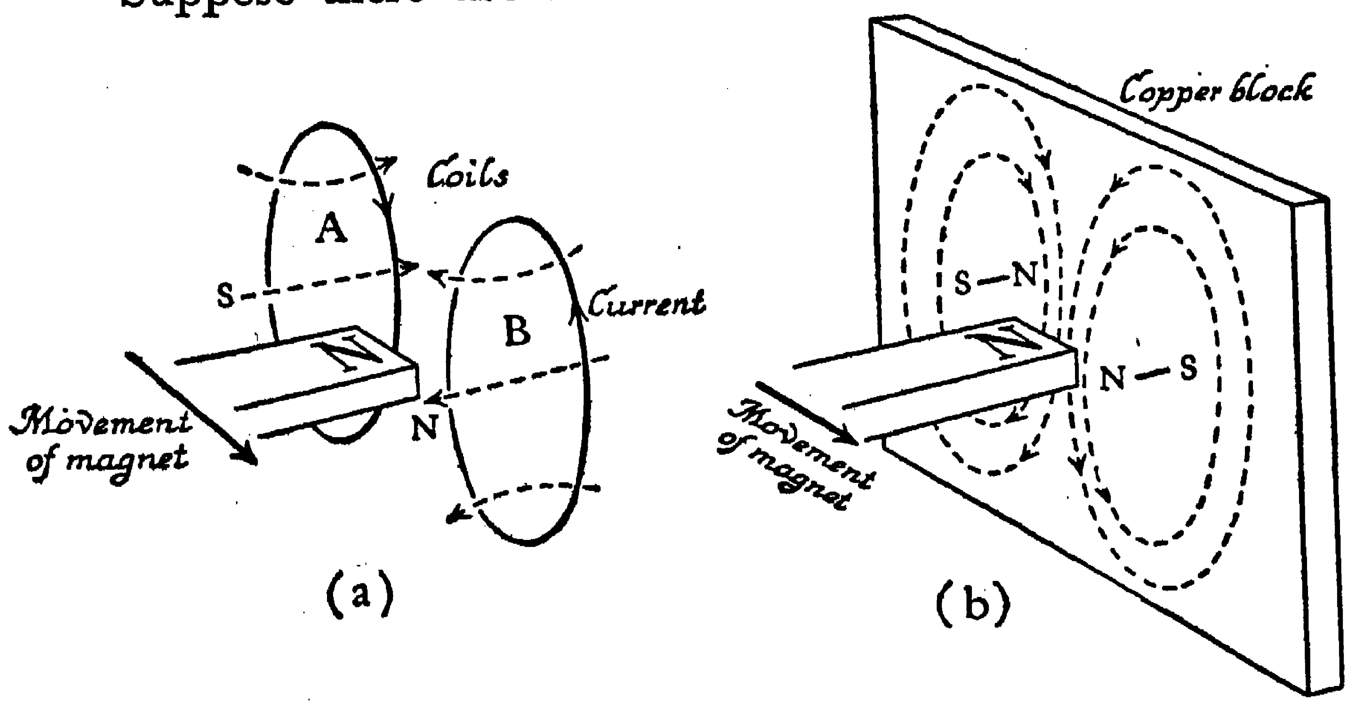


Fig. 78. The creation of eddy currents in a conductor by a moving magnet.

that a magnet is moved from a position opposite A to one opposite B, as in Fig. 78*a*. What will happen? A current will run in A, which tries to hold the magnet back, and one will run in B, which tries to prevent the magnet approaching – by our law which states that the current always runs in such a direction as to oppose the movement of the magnet. Now suppose that instead of the two coils of wire we have a solid block of copper and move the magnet past it (Fig. 78*b*). Currents will run round in the block of copper as shown by the arrows just as they do round the coils, though they are

now not confined to a circular route. An eddy current is set up by the moving magnet in somewhat analogous fashion to the water eddy around the

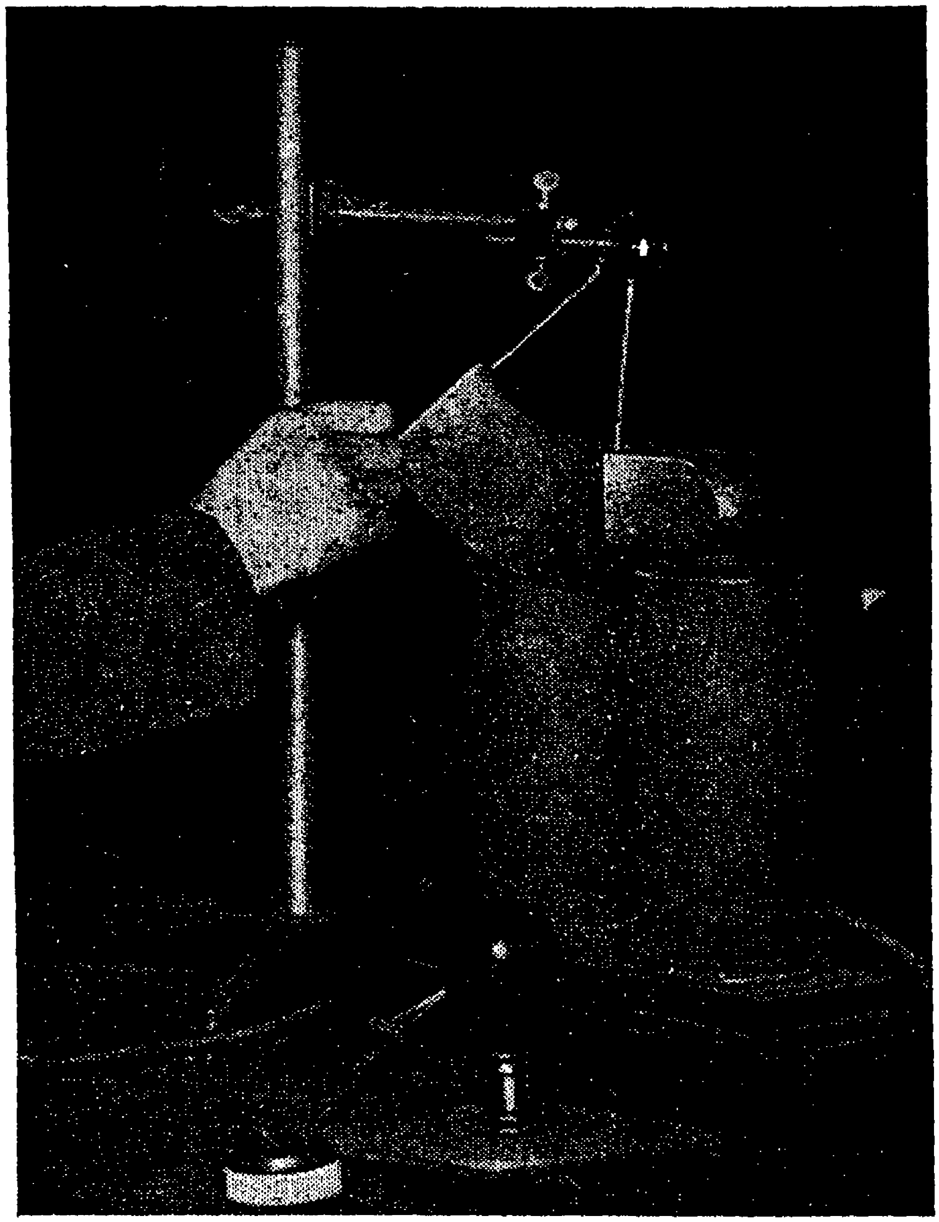


Fig. 79. The braking of a swinging copper plate by eddy currents. (*'Sphere' photograph.*)

moving blade of an oar. The eddy current is in such a direction that it opposes the movement of the magnet.

The consequence is that when a magnet is moved past a conductor, such as a sheet of metal, or the conductor is moved past the magnet, there is a reaction

between them resembling friction, a kind of sticky drag. Fig. 79 shows a way of illustrating this effect. A copper plate is swinging between the poles of an electromagnet. When the current in the electromagnet is switched on, the plate stops swinging to and fro and slowly oozes back to rest. In Fig. 52*a* (Plate 13) of Professor Blackett's large electromagnet you will see a solid aluminium ball falling between the pole pieces.

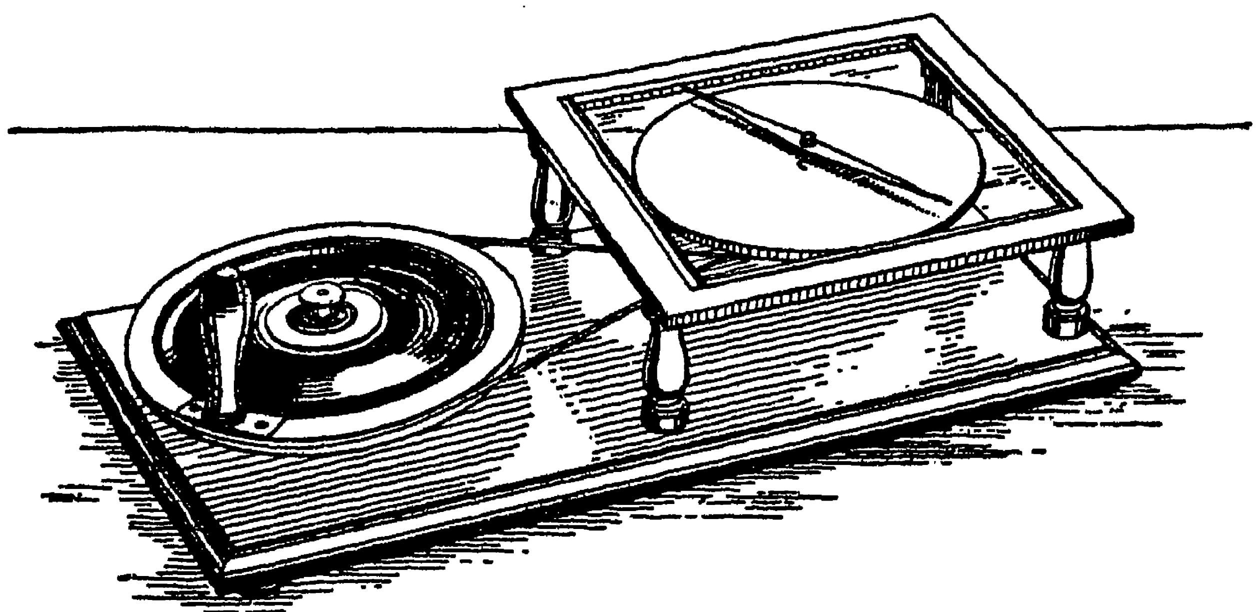


Fig. 80. Arago's experiment. A spinning copper disc beneath a sheet of glass drags round the compass needle above the glass.

When the magnet is 'on,' the ball drifts like a thistledown, or as if it were falling through thick treacle. In all these cases eddy currents are set up in such a direction that any movement of the conductor is strongly opposed.

The effect was observed by Arago before Faraday's great experiment on electromagnetic induction, and in fact Arago's observation was partly responsible for guiding Faraday in the right direction. Arago found that if a copper disc were placed beneath a compass needle and rapidly rotated, the needle appeared to be dragged round by the disc (Fig. 80). This is still the

case when a glass plate is interposed between disc and needle, so that there can be no question of air currents affecting the needle. He was led to the discovery by noticing that a compass needle in a box with a copper bottom only made a few oscillations before coming to

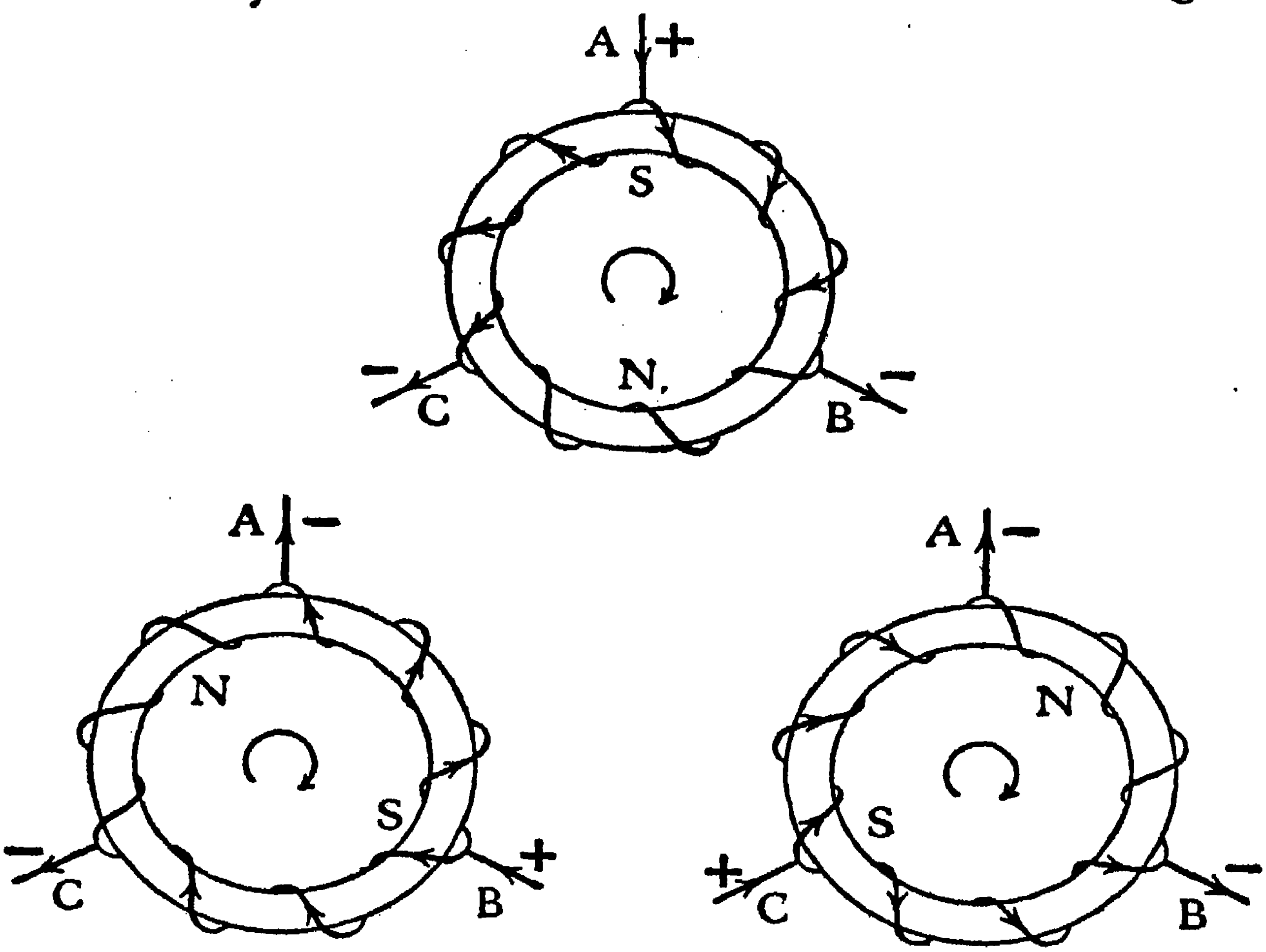


Fig. 81. The creation of a rotating magnetic field by a three-phase current, the three leads being connected to the coil at A, B, C.

rest, as if there were a drag between copper and needle, instead of several hundred oscillations, as it did when suspended in the open.

A fascinating way of illustrating eddy currents is by means of a rotating field produced by three-phase current. An iron ring is wound with an endless coil, and wires are connected to the coil at three points A, B, C (see Fig. 81). Suppose now that we lead current in at A, and out at B and C. The ring is

magnetized with an S pole at A and an N pole opposite A. If the current enters at B, the S pole shifts to B, and so also for C. The coil is now connected at A, B, C to the three terminals of a three-phase supply. You will remember that each terminal of a three-phase supply becomes the positive terminal in turn. The consequence is that the current enters first at A, then at B, then at C. If the alternating frequency is 50 cycles, the north and south poles run round the ring 50 times a second, producing a *rotating magnetic field.*

A shallow bowl of wood or papier mâché is laid on the ring, and a metal ball placed in it. It immediately starts to rotate, and accelerates till it approaches the angular velocity of the field. A metal egg will spin and get up on end. If a copper ring is held in the field one can feel it trying to twist out of one's hand, and directly it is let go it joins the dance. Eddy currents are dragging it round, making it follow the magnetic field.

If you look at the iron core of the armature of a motor or dynamo, you will notice that it is not a solid piece of iron but is built up out of many thin sheets insulated from each other. This is done in order to prevent eddy currents when the armature spins between the poles of the field magnet. If the eddy currents were allowed to flow in the iron they would heat it and fritter away energy.

Fig. 82 shows the way in which eddy currents are used to drive one type of alternating current meter. In Fig. 82*a* (Plate 20) the disc and the magnets which drive it have been removed from the meter and mounted separately. The disc turns freely on a vertical spindle. Now if we were to take a powerful magnet and move it along the surface of the disc near the edge as if

stroking it, but without actually touching it, the disc would rotate because of the reaction of the eddy currents. The disc in the meter is being 'stroked' round in a similar way, but instead of using a moving magnet the same effect is produced in an ingenious way by the stationary double magnet seen at the back

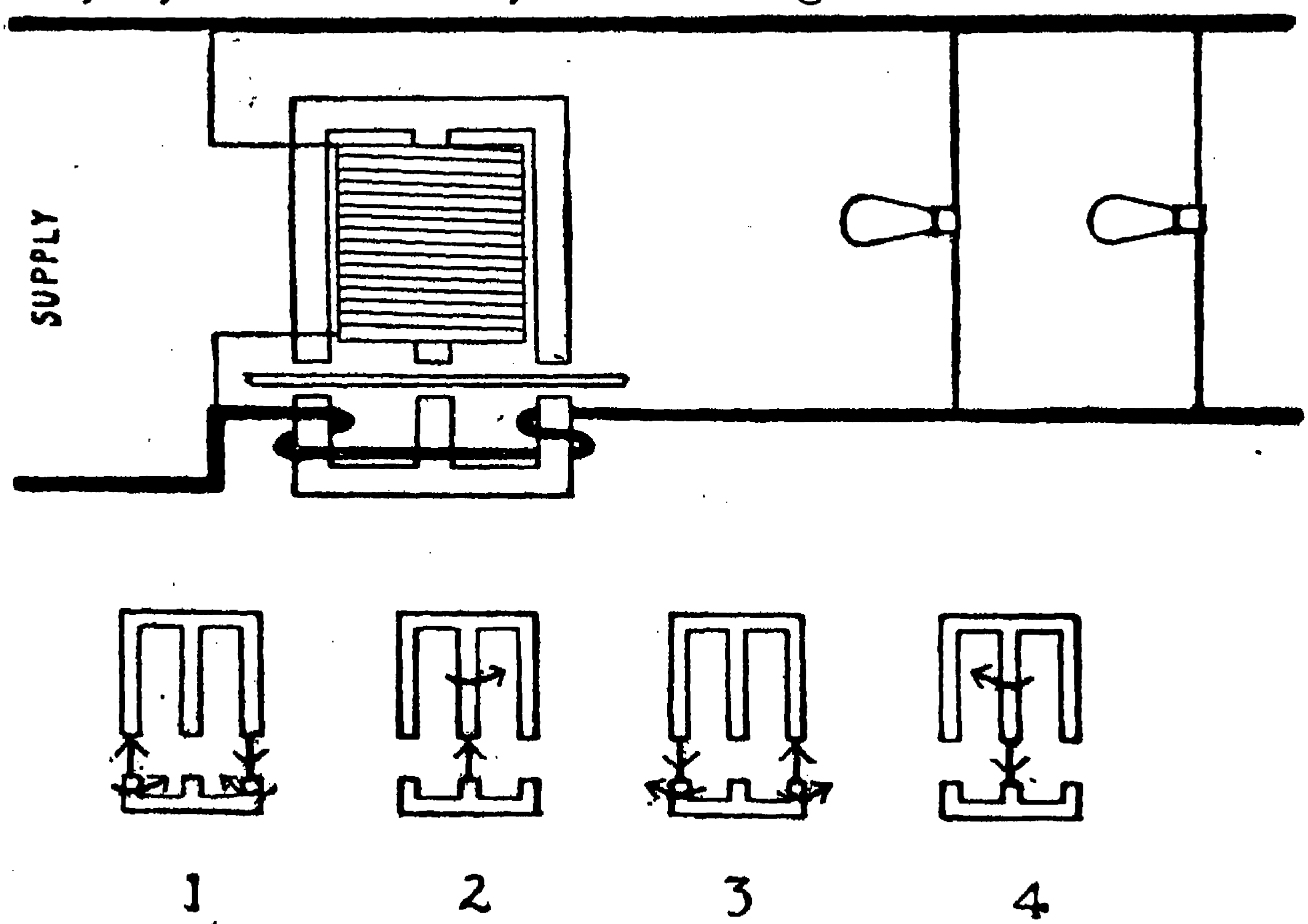


Fig. 82b. Action of alternating current meter. The series of events represented by 1, 2, 3, 4 repeats in each cycle.

of the disc. The alternating current supply, passing through the double magnet, sets up a *moving magnetic field* just as if magnetic poles were continually passing over the disc from left to right.

Two electromagnets, each with three prongs, are placed opposite each other above and below the disc, as in Fig. 82*b*. The alternating current which is to be measured flows round the coils on the outer arms of the lower magnet, making first one north and the

PLATE 20

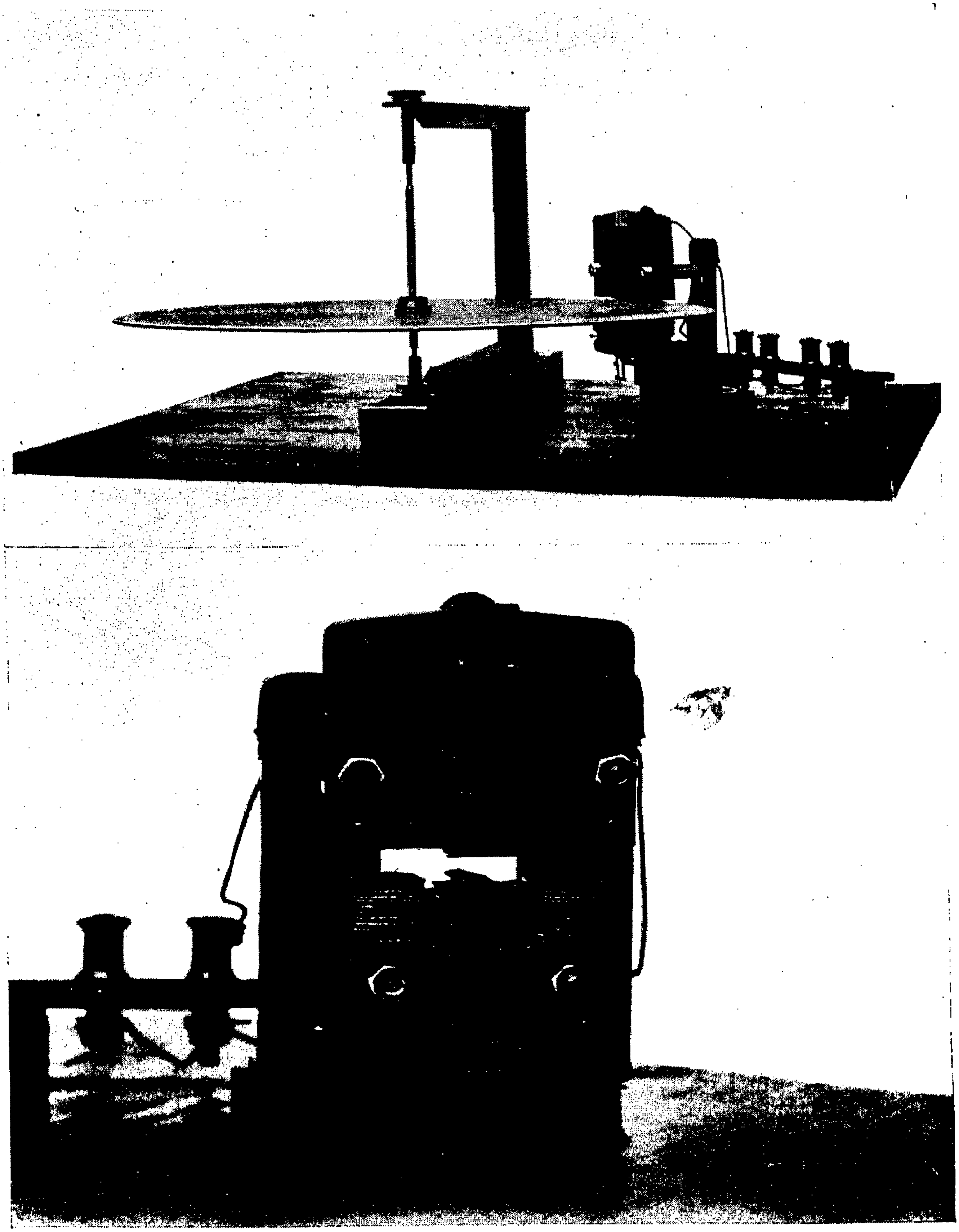


Fig. 82*a*. Disc and electromagnets of an alternating current meter. The electromagnets are shown enlarged below

[*p.* 170

PLATE 21

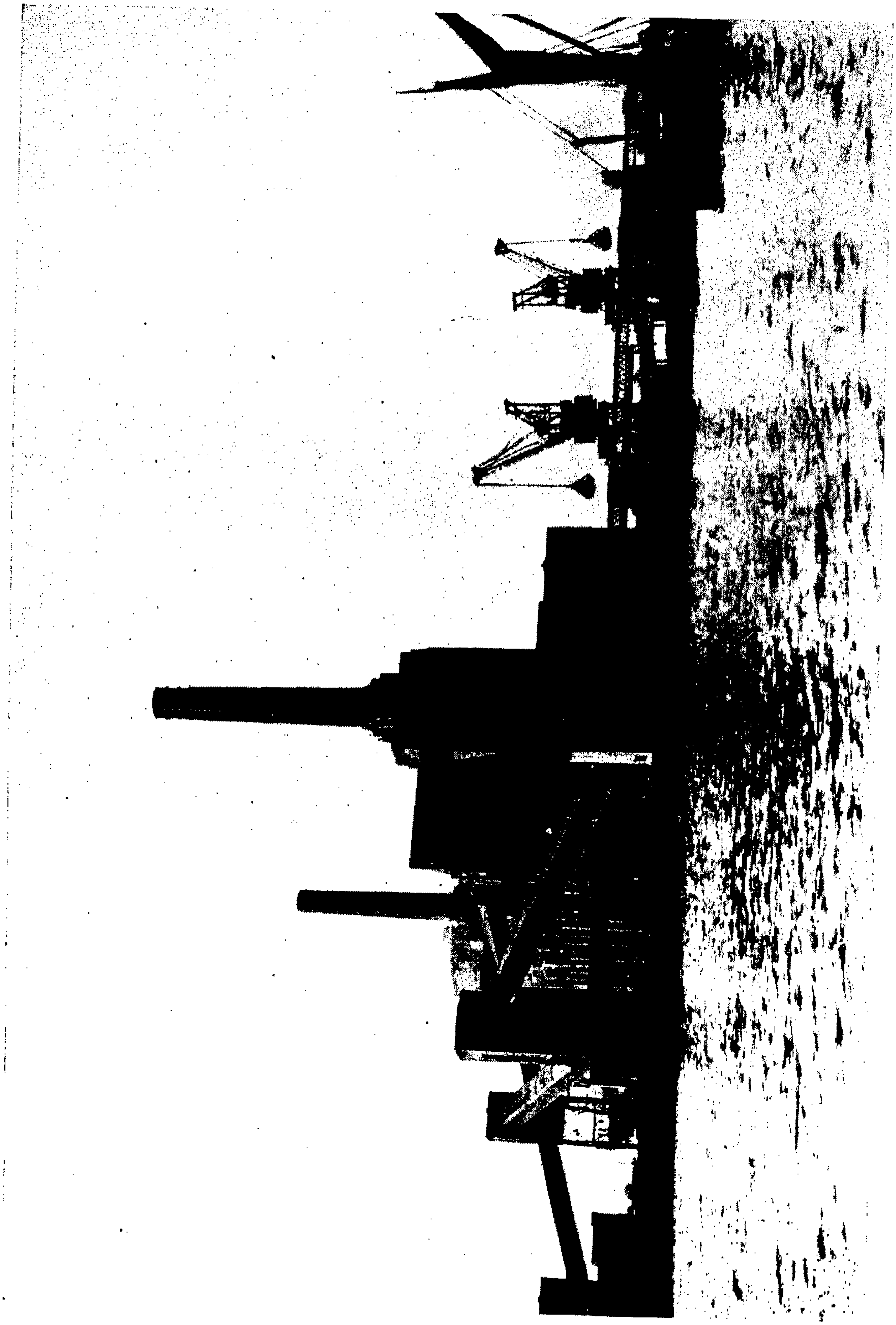


Fig. 83. Battersea Power Station. The ramps on the left convey coal (*Central Electricity Board*)

other south, and then reversing the poles, in each alternation. The upper magnet has only got a single coil with many turns on its middle prong. The alternating voltage of the mains across this coil makes this central prong alternately north and south. However, the effect of induction in this coil with its many turns is so strong that the magnetization is always lagging behind the applied voltage. You may remember the argument we used in the case of the transformer. The voltage tries to magnetize the coil, but is opposed by a back E.M.F. due to induction. The current only gets going just as the applied voltage is dying away and about to change direction. The current goes on even after the applied voltage has changed direction, and is only stopped when the latter has its maximum value in the reverse sense. The current then reverses, and continues in the reverse direction after the E.M.F. has changed back again.

The current behaves, in fact, like the clown in the circus who is trying to help the attendants. He always realizes too late what they are going to do, and rushes to the place to find that they have already done it! The current is 'slow in the uptake' because of the effect of induction.

The magnetic effects may be followed by studying in Fig. 82*b* the series of events 1, 2, 3, 4, which take place during each cycle. In 1 the lower wire from the supply is positive and a current is being driven round the lower electromagnet and through the lamps to the upper wire. In 2 the current in the lower magnet has ceased, but as we have seen the current in the upper magnet is at its greatest. The centre prong is therefore magnetized. Similar events in the reverse

direction happen in 3 and 4. The vertical arrows show the direction of the magnetic field in each case. Now if you will follow the arrow pointing upward in 1, which is on the left-hand side, you will note that in 2 it has moved to the middle and in 3 has moved to the right-hand side. The downward arrow starts on the left-hand side in 3, moves to the centre in 4 and then to the right as in 1. The transition from 1 to 2, or 2 to 3, is, however, a gradual one, and not abrupt as in the figure. It is just as if we were stroking the disc with a series of magnets passing from left to right though nothing is actually moving. The stronger the current in the lower magnet, and the higher the voltage driving current through the upper magnet, the greater is the effect on the disc and the faster does it rotate.

The disc is braked by eddy currents, caused by a permanent magnet whose poles are on either side of it (see Fig. 1). When properly designed, the rate of rotation is accurately proportional to the power. The rotations of the disc move the wheels of a counter (Fig. 1) like the cyclometer which counts the revolutions of a bicycle wheel, and this registers the total number of units which have passed through the meter.

Sufficient principles are involved in the construction of this humble instrument to illustrate a whole text-book of Electricity and Magnetism.

6. POWER STATIONS

A Power Station or Generating Station is a place where mechanical power is generated and turned into electrical power. With very few exceptions, the mechanical power is obtained either by using coal to raise steam or by using the energy of falling water.

Most generating stations in this country, such as the Battersea station shown in Fig. 83 (Plate 21) are steam stations. In former days the steam drove reciprocating engines with cylinders and pistons, but this type has now been superseded by the turbine. A turbine and dynamo are placed end to end with their shafts coupled together, and the combination is called a Turbo-generator.

There is a fine description of the steam turbine in the book *Engines* which Professor Andrade wrote after giving the Christmas lectures at the Royal Institution three years ago, which I warmly recommend you to read if you want to know more about it. I will just remind you that a turbine is a windmill blown round by steam. The rotating part of a turbine, removed from the outer case, is shown in Fig. 84 (Plate 22). The high-pressure steam enters at one end of the turbine and blows against the first set of moving blades set at an angle like the vanes of an iron windmill. It then passes through a set of stationary blades fixed to the outer case, which serve the purpose of directing the steam blast, which has been deflected by the first set of moving blades, back to its former course and on to the next set of moving blades. It passes alternately through moving blades and fixed blades, expanding as its pressure falls, so that the blades have to be made bigger and bigger. Generally there are two turbines, high-pressure and low-pressure. You can see in Fig. 85 (Plate 22) which shows a turbo-generator in Battersea Power Station, the steam pipes leading from the one to the other. The gale of steam through the turbine, to quote from Professor Andrade's account, may be 75 miles an hour when it enters and 300 miles an hour when it comes out after

expansion, taking about one-sixteenth of a second to go the length of the turbine.

The steam which has done its work passes straight into a condenser, where it turns back into water. It is condensed by coming in contact with pipes through which water is flowing. A large generating station needs about fifteen million gallons of cooling water each hour. It is as important to place a steam station where this water is available as to have a convenient supply of coal. Battersea, for instance, uses the water from the Thames, and Barton uses the Manchester Ship Canal.

The turbine has many advantages as a means of driving a dynamo. It rotates smoothly at a high speed, and as a high speed is also suitable for a dynamo the two can be coupled directly together. It has a high efficiency. A turbine turns about twenty-eight per cent of the energy of the burning coal into useful work, as compared with ten per cent for a first class railway locomotive. This comparison is, of course, not quite fair to the locomotive which cannot carry a condenser. A big power station uses just over one pound of coal to generate a 'unit,' i.e. a kilowatt for an hour. A striking feature of a turbo-generator is its compactness. It is hard to believe that so much power is being developed in so small a space.

A station which derives its energy from falling water is called a hydro-electric station. If the water is coming from a reservoir at a considerable height above the station, so that it is at high pressure, it is used to drive a 'Pelton Wheel.' The water comes out as a narrow jet from a nozzle, and this jet is directed against buckets arranged around the rim of a wheel like a glorified water-wheel. Fig. 86*a* shows a diagram of

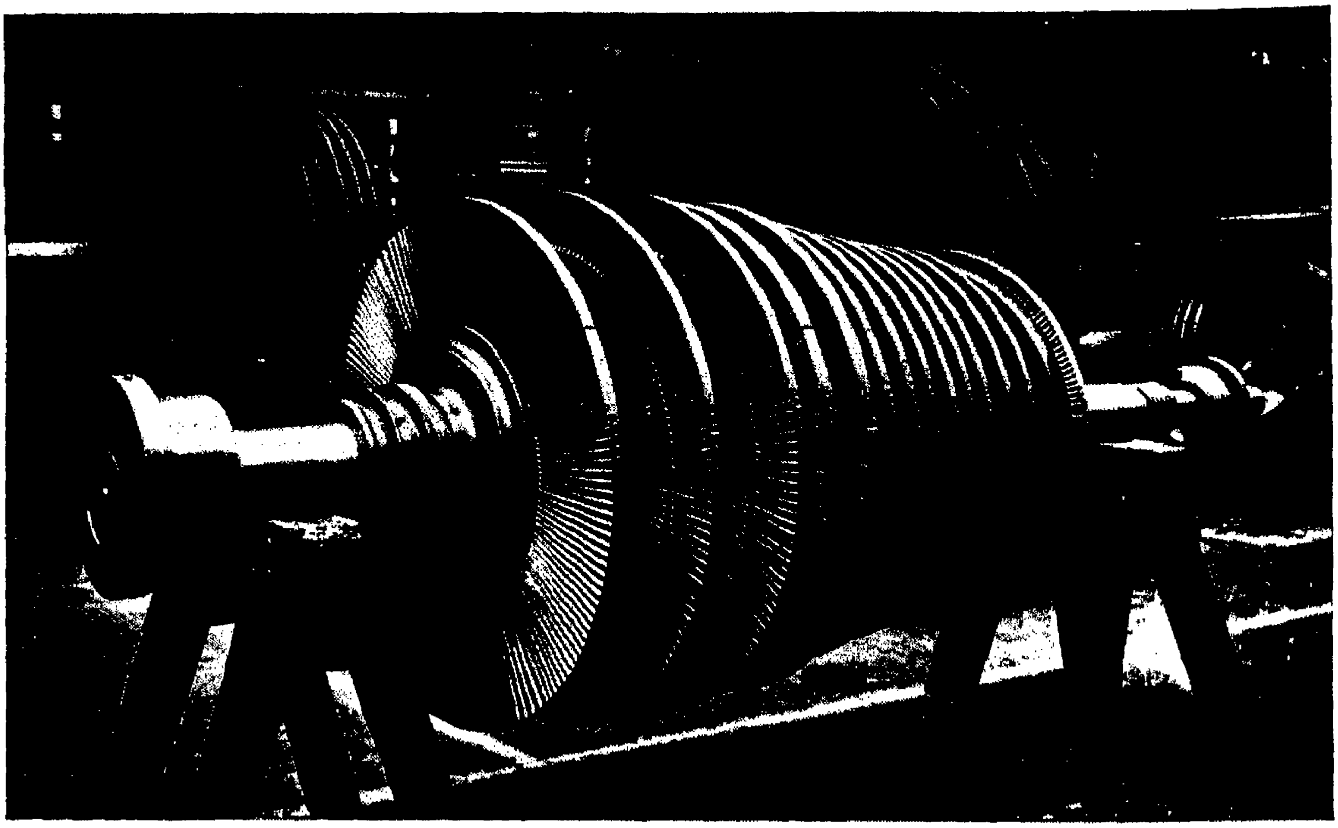


Fig. 84. Blades of a turbine mounted on the shaft (*Metropolitan-Vickers*)

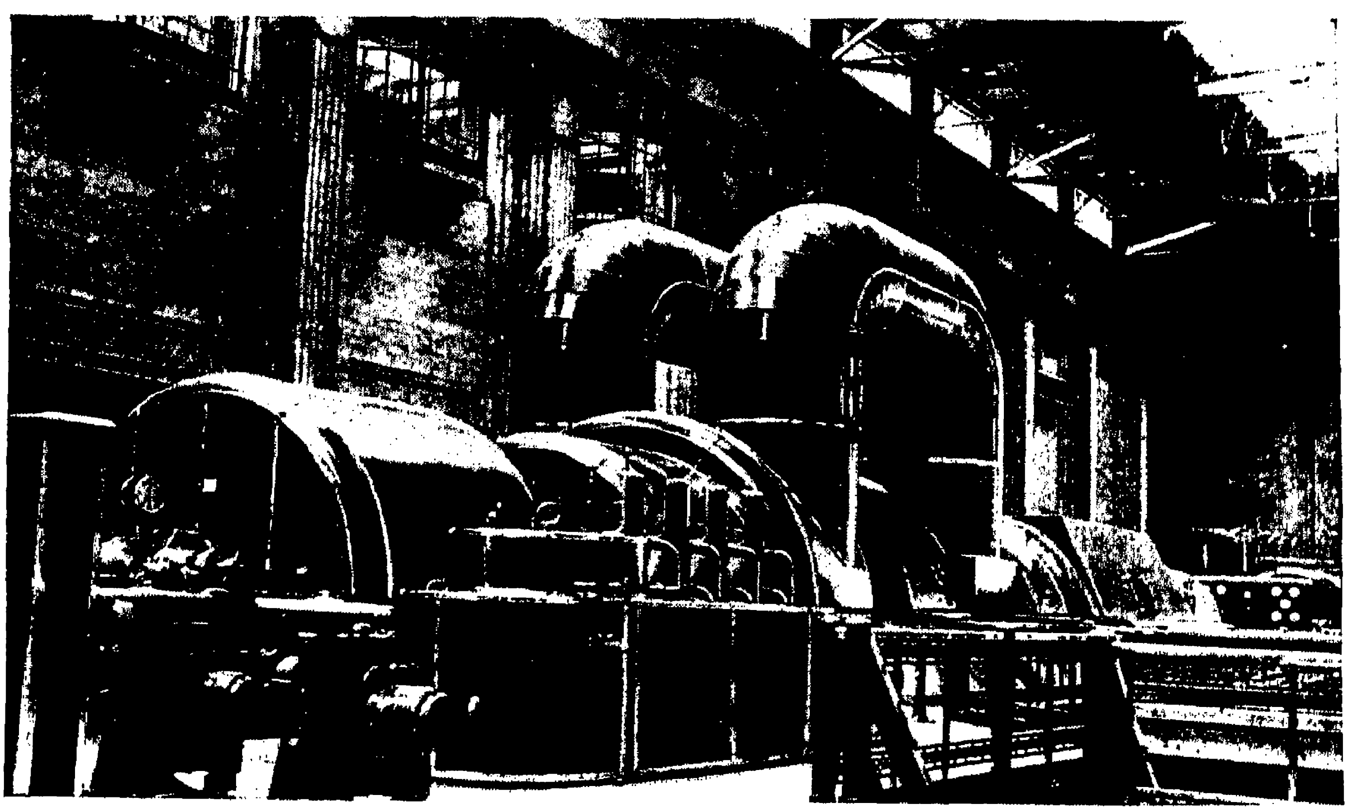


Fig. 85. A turbo-generator in Battersea Power Station (*Central Electricity Board*)

Fig. 87. The British Aluminium Company's hydro-electric station at Fort William. The photograph has been taken from between the pipes which run down the hill and are seen leading to the station in the distance (*Central Electricity Board*)

a Pelton Wheel, and Fig. 86*b* the peculiar shape of each bucket. The object of the nick at the bottom of the bucket seems mysterious at first sight. We only want the water to hit each bucket as it comes to the bottom of the wheel, and the nick allows the jet to miss the buckets which have not yet reached the bottom

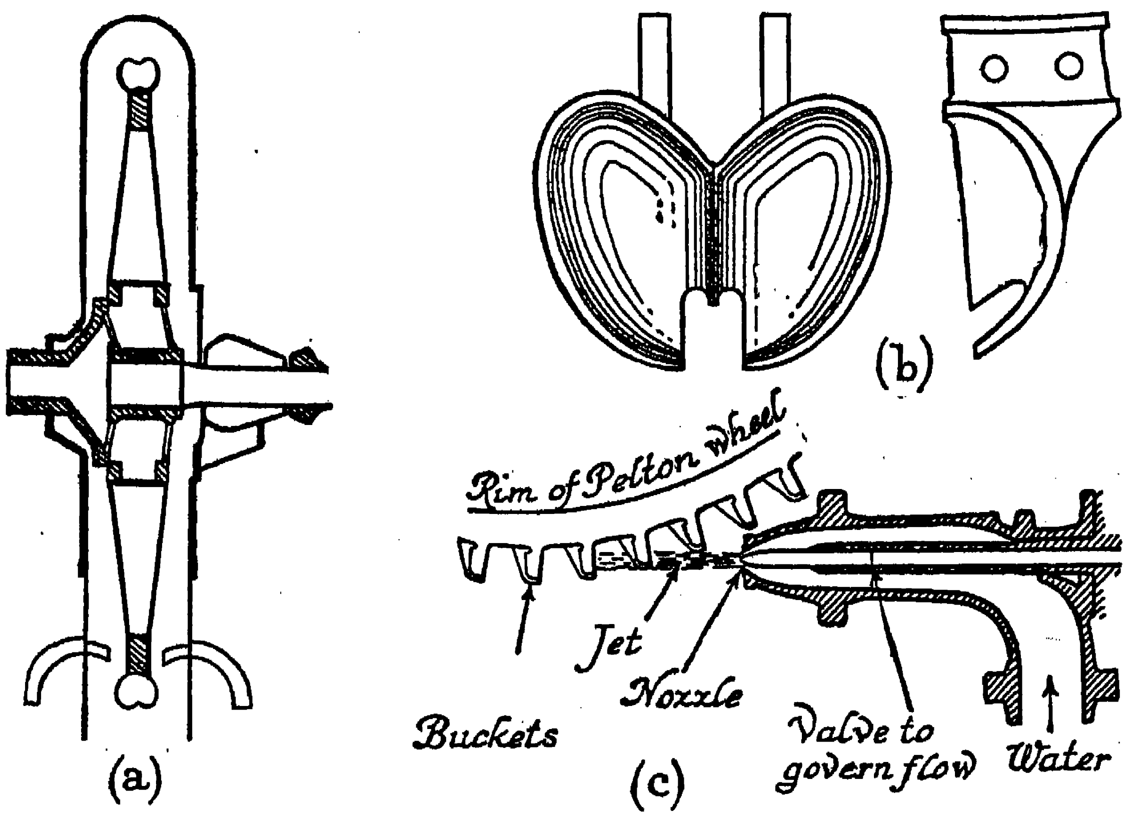


Fig. 86. A Pelton wheel. (*a*) The wheel seen edgewise. (*b*) A 'bucket' with its notched edge. (*c*) The jet hitting the buckets on the rim of the wheel. (*Gibson's Hydraulics*.)

position. Fig. 86*c* shows how the jet plays upon the buckets. If on the other hand the water is only coming from a moderate height, as at Niagara for instance, it is used to drive a turbine. There are many types of turbine and it would take too much space to describe them here. The principle is the same as that of the windmill or steam turbine, but in general the water is led in at the centre of the turbine and shoots over curved blades towards the rim, making the turbine spin round.

Opportunities of using water power mostly occur in

sparsely inhabited mountainous country where the power is not needed locally. However, now that electrical transmission of power over long distances is possible, water-power can be used. In our own country, a number of stations in south-west Scotland are being built which will pour their energy into the grid system. Fig. 87 (Plate 23) shows the pipe lines running down hill to a hydro-electric station.

To describe the dynamos in any detail would take us too far afield, but I will mention one or two features which may help you to understand what you see if you visit a large power station.

In the first place, if you go back to the diagram of the simple dynamo in Fig. 62, you will readily understand how an alternating current is generated. It is simpler to generate alternating than direct current; it is done by leaving out the commutator. Instead of pressing on a divided commutator, the brushes may touch conductors called slip rings, each end of the armature winding having a slip ring and brush of its own. We have seen that the induced current in the armature rushes first one way and then the other, and if we do not rectify this current by a commutator it will be sent out as alternating current. It is more common nowadays, however, to plan the A.C. dynamo in such a way that brushes are unnecessary. Generators work at high voltages, the common ones in this country ranging from 6,600 to 33,000. The difficulty of collecting large currents at these high voltages from rotating armatures is avoided by the cunning device of turning the dynamo inside out. The armature is stationary and the field magnet goes round. The coils in which the current is induced are placed on the inner surface

of the outer frame (called the 'stator'), and the field magnet or 'rotor' spins inside. The current exciting the field magnet is relatively small and at a low voltage and is therefore easily led in by slip rings. The powerful high tension currents come from the stator windings, and as these are at rest it is much easier to insulate them. Fig. 88*a* (Plate 24) shows the rotor for one of the 105,000 kilowatt generators at Battersea being despatched on a truck and Fig. 88*b* (Plate 24) shows the casing in which the coils of the stator are placed.

A direct current dynamo can excite its own field magnets, but in an alternating current machine they must be excited by a separate supply of direct current. At the end of a big generator there is a small direct-current dynamo whose sole task is to excite the field magnets of the rotor.

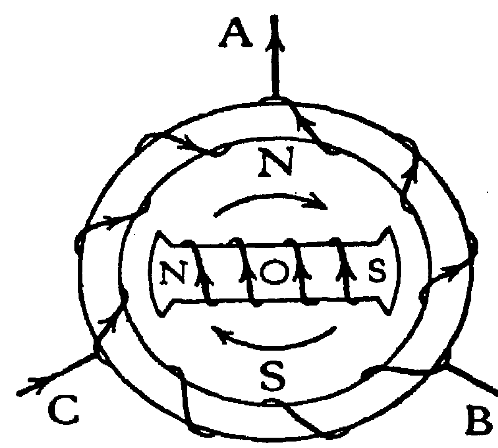


Fig. 89. A (very unpractical) way of generating three-phase current, merely illustrating the principle.

The windings of the stator are very complicated, but a simple model may serve to show how a three-phase current can be excited. We have already seen (page 168) that if a three-phase supply is fed into three points of a coil round a ring, a rotating magnetic field is produced. This works backwards. If a magnet is rotated inside the ring, a three-phase voltage is generated. In Fig. 89, suppose a powerful electromagnet is rotating inside the ring. What current will be induced in the coils? It is always safe to give the general answer; it will be a current which *opposes the motion*. As the magnet turns, the induced current

will make north and south poles in the ring which rotate ahead of those of the magnet and tend to push it back. We have already seen that a current which produces such a field is a three-phase current. The current will come from the leads in the order A, B, C, etc. We have, in fact, designed a crude three-phase dynamo, with the coil as stator and the central electro-magnet as rotor.

When a number of generators are feeding alternating current to the same mains, they all automatically keep step like soldiers, timing their impulses of current so that they occur simultaneously. If one generator falls a bit behind in its timing, the current from the others tends to speed it up as if it were a motor. If it gets a bit ahead, it does more than its share of the work till it falls into line again. When it is required to add an additional generator to those already working, it is speeded up till an instrument with a big dial informs the operator that it is keeping time with the running machines. It is then switched on to the 'bus-bars,' or common terminals of the main supply, and settles down into the collar along with the rest of the team. Hitting off the right moment to close the switches is rather like making a quiet gear-change in a car.

7. THE LOAD ON A POWER STATION

The amount of electrical power which is used varies considerably during the day, and it is different in summer and winter. To illustrate this, I have obtained from the Barton Power Station in Manchester graphs showing the output on two typical days, 5th July and 16th November, 1934. The hours run from left to right on the diagram, starting from midnight. The

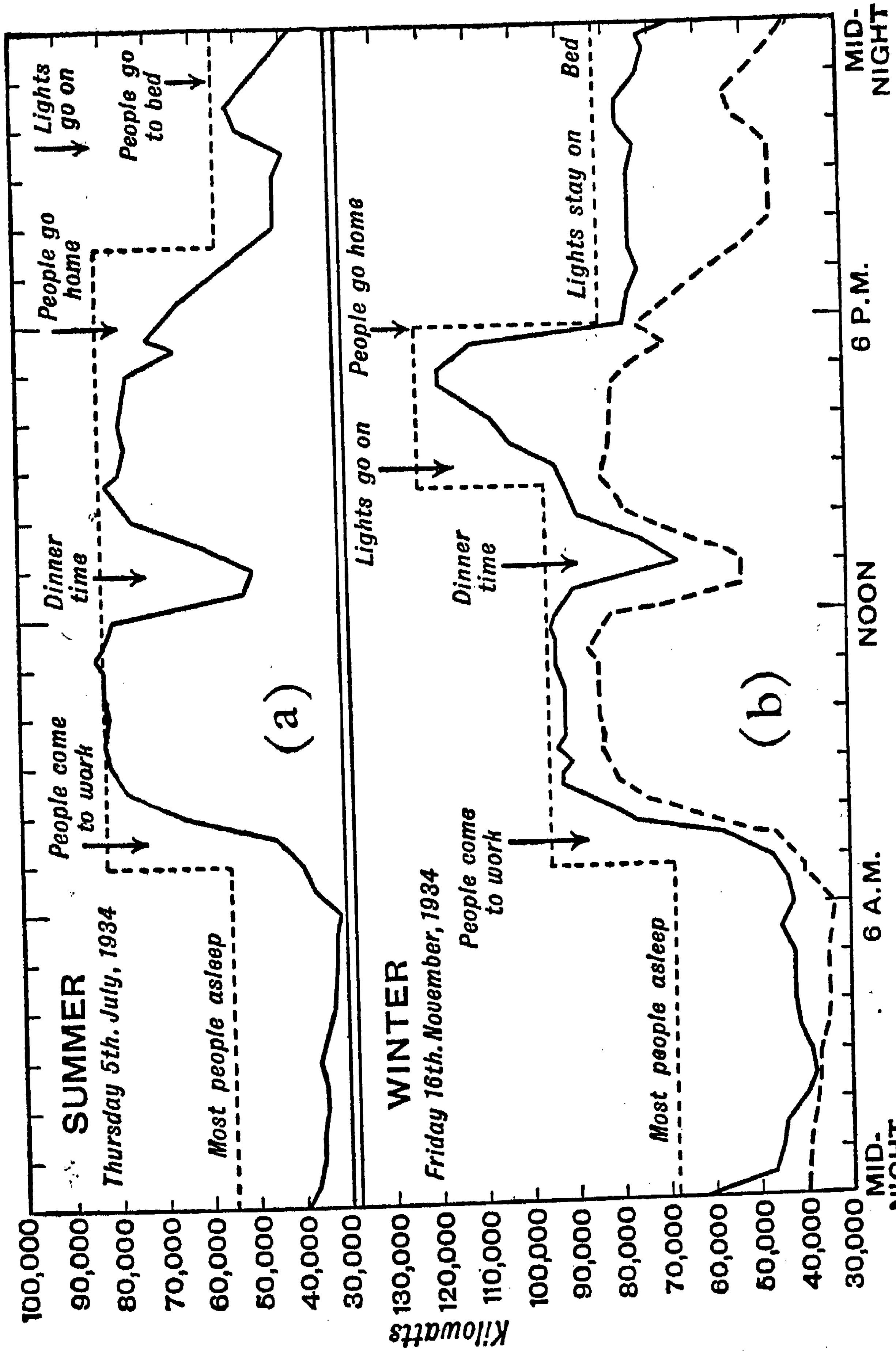


Fig. 90. The fluctuating demand for electrical power, during typical 24-hour periods in summer and winter. (*Barton Power Station, Manchester.*)

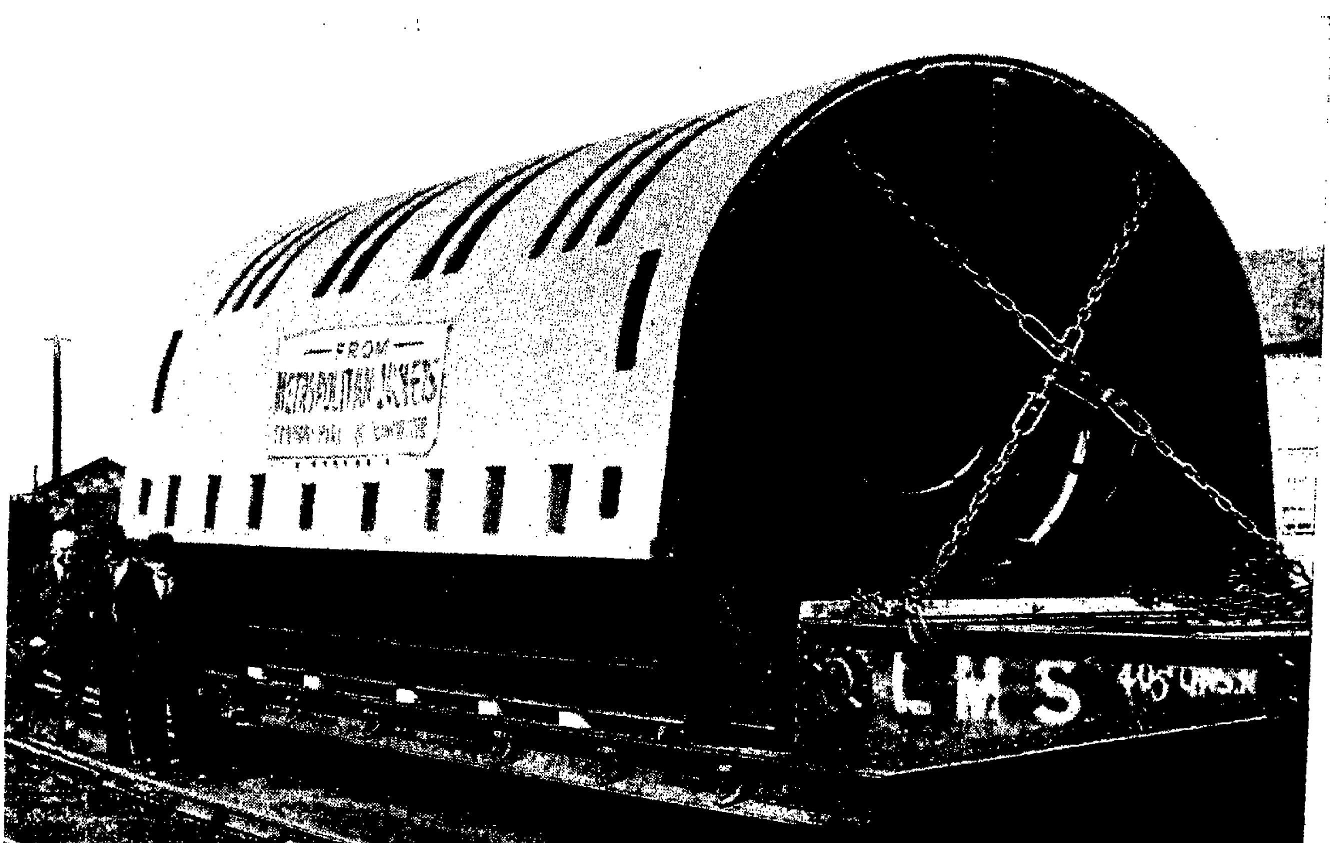
output is measured in mega-watts, a mega-watt being 1,000 kilowatts or about 1,300 horse-power. Taking the summer day first (Fig. 90*a*) you will see that from midnight to 7 a.m. little current is used. Between 7 and 8 there is a sharp rise because people go to work and machines in factories are set in motion. The demand is continuous during the morning till the factory hooters sound at 12 mid-day. The machines stop, and everyone hurries off to lunch. At one o'clock the output rises again as work is resumed, but it may perhaps be significant that the rise is more gradual than the sudden drop at 12! Between 5 and 6 in the afternoon work ceases and people go home. As it is nearly midsummer, they do not need to light up their houses and the current remains low till nearly ten o'clock when there is a little peak after sunset. Manchester is a sober and industrious city, and not a gay metropolis like London, so you will notice that soon after this everyone goes to bed.

In winter (Fig. 90*b*) the current is much the same in the small hours, but is considerably higher after 8 a.m. The winter gloom makes it necessary to use a good deal of electric light in factories, shops, offices, and homes during the day. You will see the same fall at lunch-time. At half-past three it becomes dark, and all the lights go on, giving a tremendous peak. This is the heaviest load the station has to cope with. It remains high after work is finished, because extra lights go on in the houses, and it does not drop till people go to bed and the street lights are reduced between 11 and 12. The records of the station are like a little history of everyone's habits.

The upper dotted line shows how the load is sustained.

PLATE 24

(*a*)



(*b*)

Fig. 88. The rotor (*a*) and the stator casing (*b*) of a large generator (*Metropolitan-Vickers*)

[*p.* 180

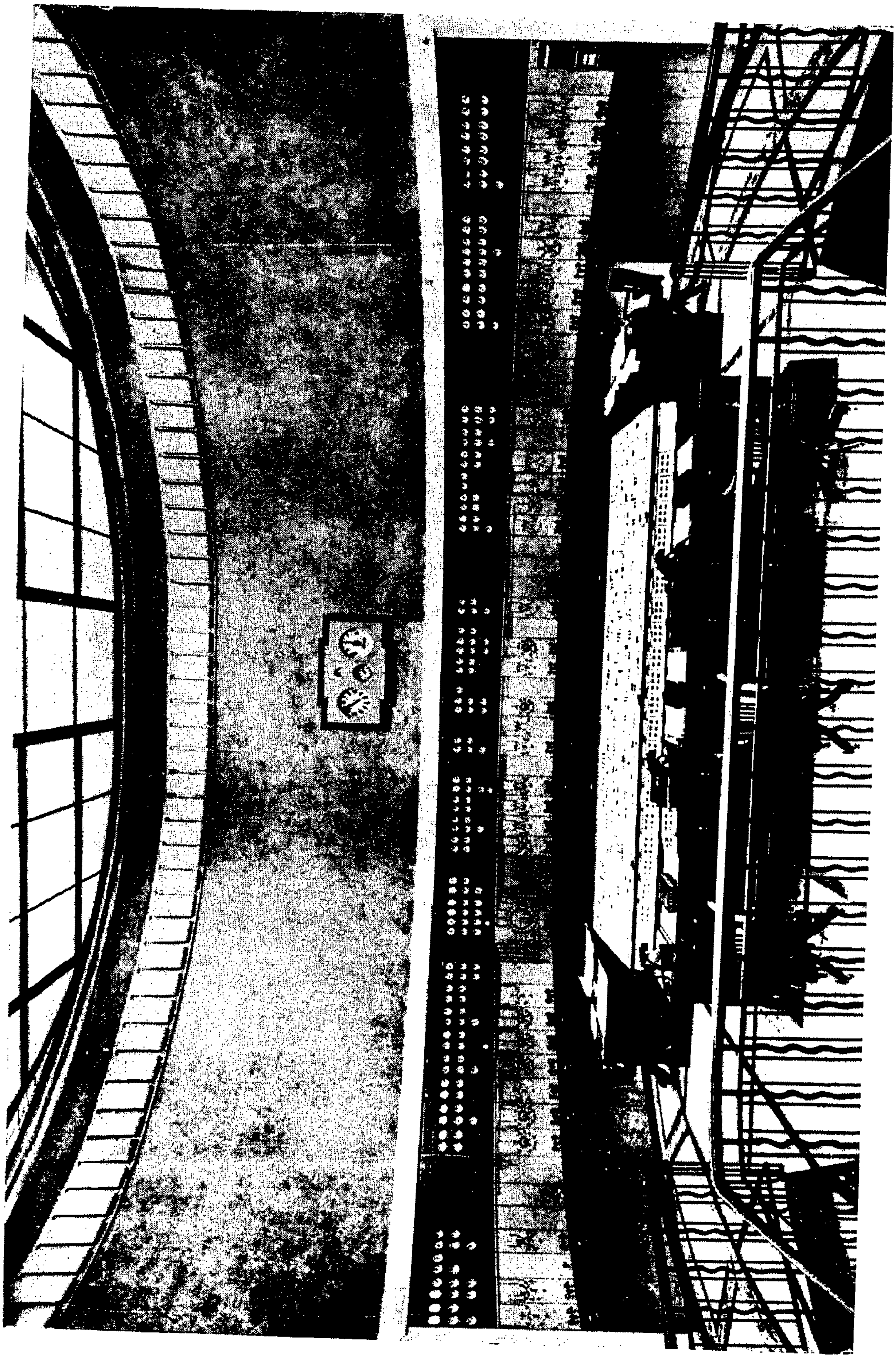


Fig. 92. The room at a control centre where the supply of power to the Grid is regulated (*Central Electricity Board*)

The power station has several big turbo-generators, but only as many are set going as are required to meet the demand for power. A step up in the dotted line shows the increase in possible output when a new generator is set in motion; the dotted line must always be above the line which indicates the demand. When an additional generator is working more steam is required, so demands must be anticipated as far as possible. The demand depends on such factors as whether it is fine or overcast, hot or cold, as well as on the time of day and the season. These graphs represent the situation when each station had to meet the fluctuations in its own local demand. Now that stations are linked by the grid, there is a scheme of central control described in the next section.

8. THE GRID

The grid is a system of high voltage transmission lines all over the country which is run by a body under public control, the Central Electricity Board. The system illustrates in a very fascinating way how the problem of providing a general supply of electrical power at cheap rates may be attacked. A map of the grid is shown in Fig. 91.

To understand the purpose of the grid, we must realize that there are two stages in electrical supply, which may be compared roughly to manufacturing and selling in other trades. There is in the first place the generation of the power and its transmission to distributing centres, or the wholesale supply of power. In the second place, lines must be laid and maintained, from these distributing centres to customers, and the current used by customers must be measured and

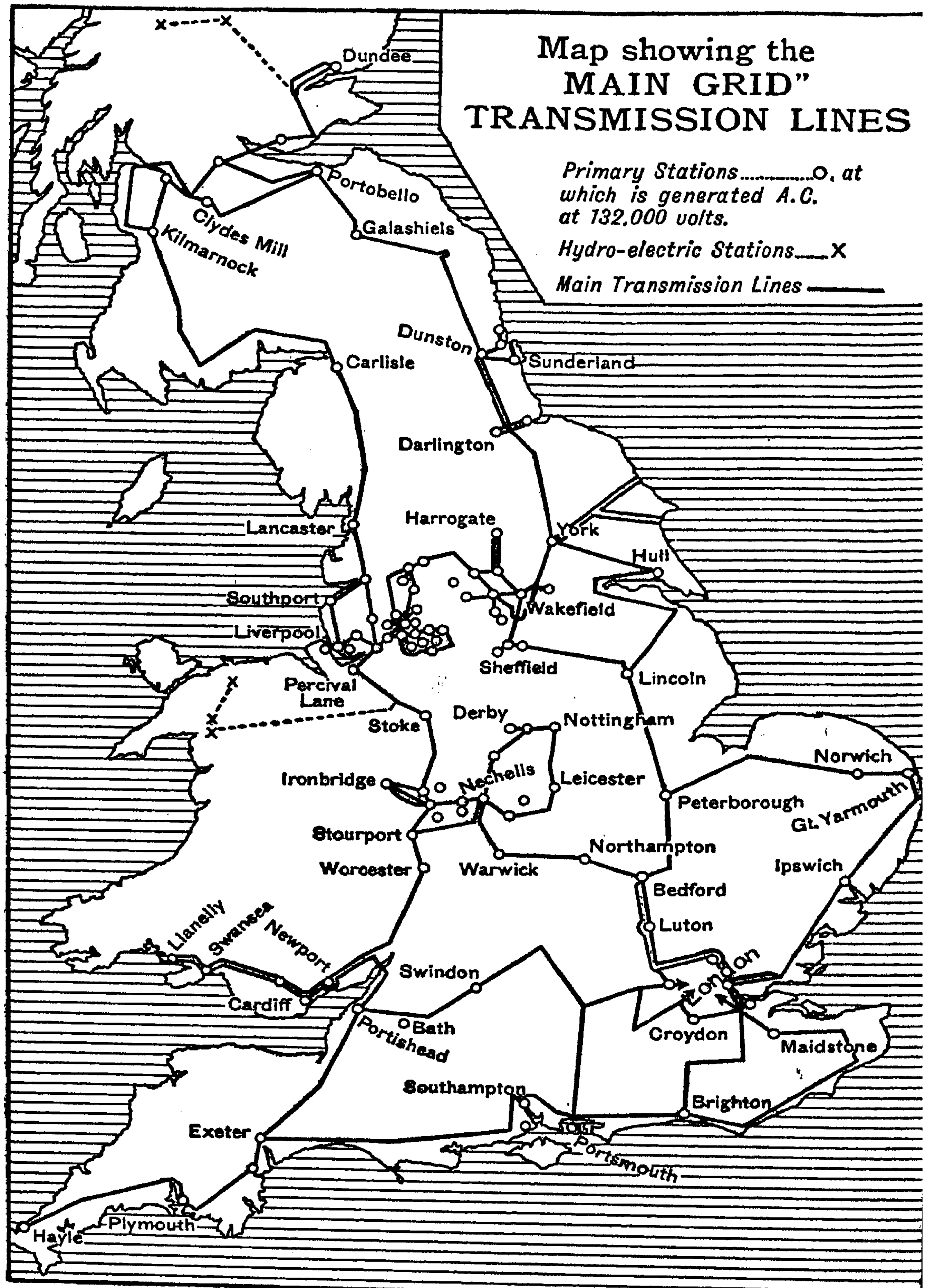


Fig. 91. A map of the 'grid' system.

charged for, this being the retail side. As in many other trades, the cost of distribution is immensely greater than that of production. Electrical power in bulk is astonishingly cheap; the tariff fixed by the Central Electricity Board varies somewhat from one area to another, but in the North-western area for example, the running charge is one fifth of a penny for each unit of a kilowatt-hour.[1] When we pay the quarterly bill for 'Electricity' a very small fraction of the charge represents the cost of the electrical power we have used. What we are really paying for is the cables, wiring, meters, and services which make the power available to us. Domestic tariffs vary in different parts of the country, but perhaps I may take that in my own neighbourhood as an example. In every £10 of my bill, just over £1 represents the cost of producing the electrical power I use. The remaining £9 is paid for the privilege of being able to switch on the light when I like. As consumers, we are like people who have hired a box at the opera for the whole season and only visit it two or three times, or who keep a taxi waiting all day in case they should need it. If we all used our supply to its full extent continuously, the cost per unit would be extremely small. It costs much more because we only use it at odd times, and, worse still, we all want it at the same time, producing the big peaks in the load which have to be coped with by the supply stations.

Before the grid was built, many local supply undertakings both produced their power and sold it to their customers. Each station had to have a sufficient

[1] This rate is practically doubled by a fixed charge made by the Board to meet the interest on their capital expenditure on plant.

reserve of machinery to meet its peak load. Though large stations produced power cheaply, many of the small stations were very inefficient. Some produced direct current, some alternating, voltages varied, and frequencies varied, so that customers had to buy lamps and motors to suit their particular local supply.

The change made by the grid scheme is briefly as follows: Each local undertaking still has control of the lines to its customers. It fixes retail tariffs and collects payment. On the other hand, responsibility for the production of electrical power has been taken over by the Central Electricity Board. Though the big supply stations still run their generators, they are under the control of the Board, which has in effect bought up the manufacturing side, and sells energy again to the retailers to distribute to their customers.

In order that it should be possible to pool the electrical supply in this way, each generating station is linked to the grid by transformers. We can think of it most simply by imagining the generators pouring their energy into the grid, under the control of the Board, and supply undertakings drawing energy from the grid and paying the Board for it. Actually it seems a bit more complicated in many cases because the generating stations feed local customers' lines direct without passing the energy into the grid and then drawing it back again, but this is only a matter of book-keeping. If the local generators are not working at all, the supply company draws all its energy from the grid through the transformer. If the generator is working full steam ahead, and the local demand is light, it is pouring its extra energy into the grid through the same transformers.

What is the object of this? It is done in order to meet the demand in the most efficient way. Formerly each station had to keep its machines running the whole time, raising more steam when the demand was heavy and slacking off when it got light. Now the stations are marshalled in groups, like soldiers being brought into action under the orders of a general. The huge stations work day and night at full power, meeting what is called the 'Base Load.' The next group of stations, called 'Two-Shift Stations,' are shut down at night and at the week-end, when the demand is light. Finally there is a group of reinforcements called Seasonal Stations, which are only called up during peak-load time in winter (see Fig. 90) and are shut down all the summer. The most efficient stations work the whole time, and the least efficient only for a short time. Many of the smaller undertakings have shut down their generators altogether and just act as retailers, buying power from the grid and selling it to their customers. It is much easier for a new supply company to start, because it need not build a generating station. It can link on to the grid and set up shop.

The way in which this pooling of power is carried out is very fascinating. There are two sides to it, the central control and the grid links between stations.

The country is divided into areas, each with its own network of lines to which all stations in that area are linked, and with a control centre which is like the brain of the organization. If one goes into a control centre one sees a vast array of dials on panels in front of the engineer in charge (Fig. 92, Plate 25). These dials are labelled with the names of generating stations and are recording what that station is sending into the grid or

taking from it at that moment, although the station may be a hundred miles away. There is also a big diagram of the grid to show how the stations are linked up, with red lights to indicate when switches are on and green lights when they are off. One can see exactly what is happening over the whole area.

The control station is able to forecast with fair accuracy what the demand will be at different times of the day, for the particular times of the year. It issues orders beforehand to generating stations, telling each during what hours it is to run and what energy it is to produce. The extra bit, which cannot be foreseen, is taken on by one big station. All the other stations are going full steam ahead, but at this particular station the engineer has (figuratively) his hand on the throttle. If the demand goes up, he lets more steam into his turbines, if it goes down he shuts some off. Should the demand rise so quickly that he cannot cope with it, he telephones the control centre which calls up reinforcements by telling a new station to get going.

How does the man in control know when to put extra power into the grid and when to slack off? The way in which this is done reminds us of a runner or cyclist acting as pace-maker to a group. He does it by watching the *'frequency' of the system*. The normal frequency is 50 cycles, and the generators in all the stations are turning round in step with each other, for we have seen that this keeping in step is a consequence of alternating current supply. If a number of people switch lights and motors on, *all* the generators begin to run more slowly, still keeping time. The needle of the frequency meter, which you see at the centre of the control room, drops below 50, and the generators

at the pace-making stations are boosted up to get it back to 50 again. It works the other way, of course, when the demand falls.

Underneath the frequency meter is a clock with two hands. One hand is run by a chronometer which

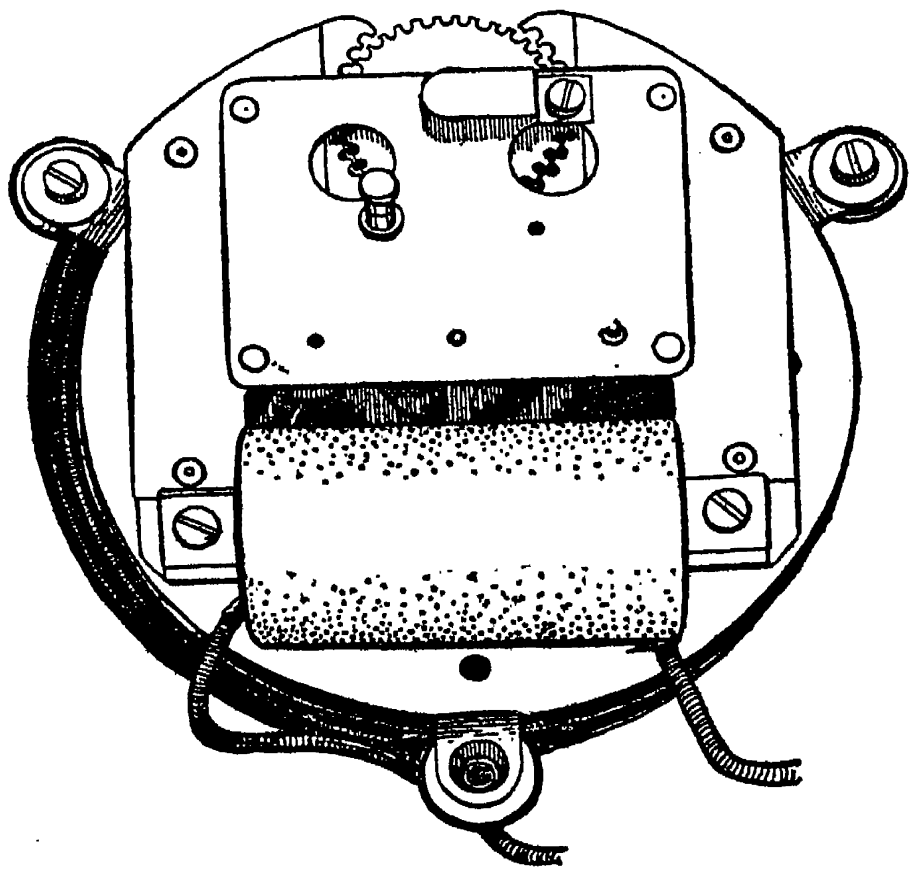


Fig. 93. An electric clock. The toothed iron wheel seen above moves on one tooth each time the alternating current excites the electromagnet with toothed poles. The wheel drives the clock hands through a chain of gears. (*Ferranti.*)

is checked against Greenwich time. The other hand is run by an alternating current motor, much as in the electric clocks which are now common (Fig. 93). If the frequency is exactly 50, the two hands will keep in step. If the electric hand falls behind the chronometer hand it shows that the generators are turning too slowly, and the grid frequency is boosted till the electric hand catches up, and vice versa. At any one moment there may be a little difference between the

two hands but this is never allowed to exceed a few seconds. That is why our electric clocks run by the alternating current supply keep such excellent time. As long as they do not stop, they *cannot* be more than a few seconds wrong. Their motors are rotating in step with the generators in the power stations, and are being forced to keep time by the whole grid system backed up by the authority of the Astronomer Royal at Greenwich.

9. TRANSFORMING AND SWITCHING SUB-STATIONS

The enclosures one sees in many places with a network of girders and wires on insulators, and rows of iron tanks beneath with porcelain horns like the antennae of immense insects, are *Transforming and Switching Sub-stations*. There is generally one outside each generating station, linking the station to the grid. Many of the sub-stations, however, are not attached to a generating station. They are merely places where energy is drawn from the grid and sent out again at a lower voltage for local supply.

A typical sub-station of this latter kind (Little Barford) is shown in Fig. 94*a*, Plate 26. It looks an extremely complicated maze, but actually it is doing a very simple job. A main transmission at 132,000 volts linking Peterboro' and Bedford runs through the sub-station. Two transformers draw energy from the main lines and transform down to 33,000 volts for local lines, which lead to various places in the neighbourhood. In the photograph the lines at 132,000 volts are seen on a tower in the foreground, and the local supply is led away from the distant end of the enclosure.

PLATE 26

Fig. 94*a*. Little Barford Transforming and Switching Sub-station (*Central Electricity Board*)

Why is it so complicated, when one would think it only necessary to join the transformer to the cables? There is so much gear because of the care which has to be taken in handling large amounts of power at high voltage. I have put a plan of the station on the opposite page (Fig. 94*b*) representing the three lines required for

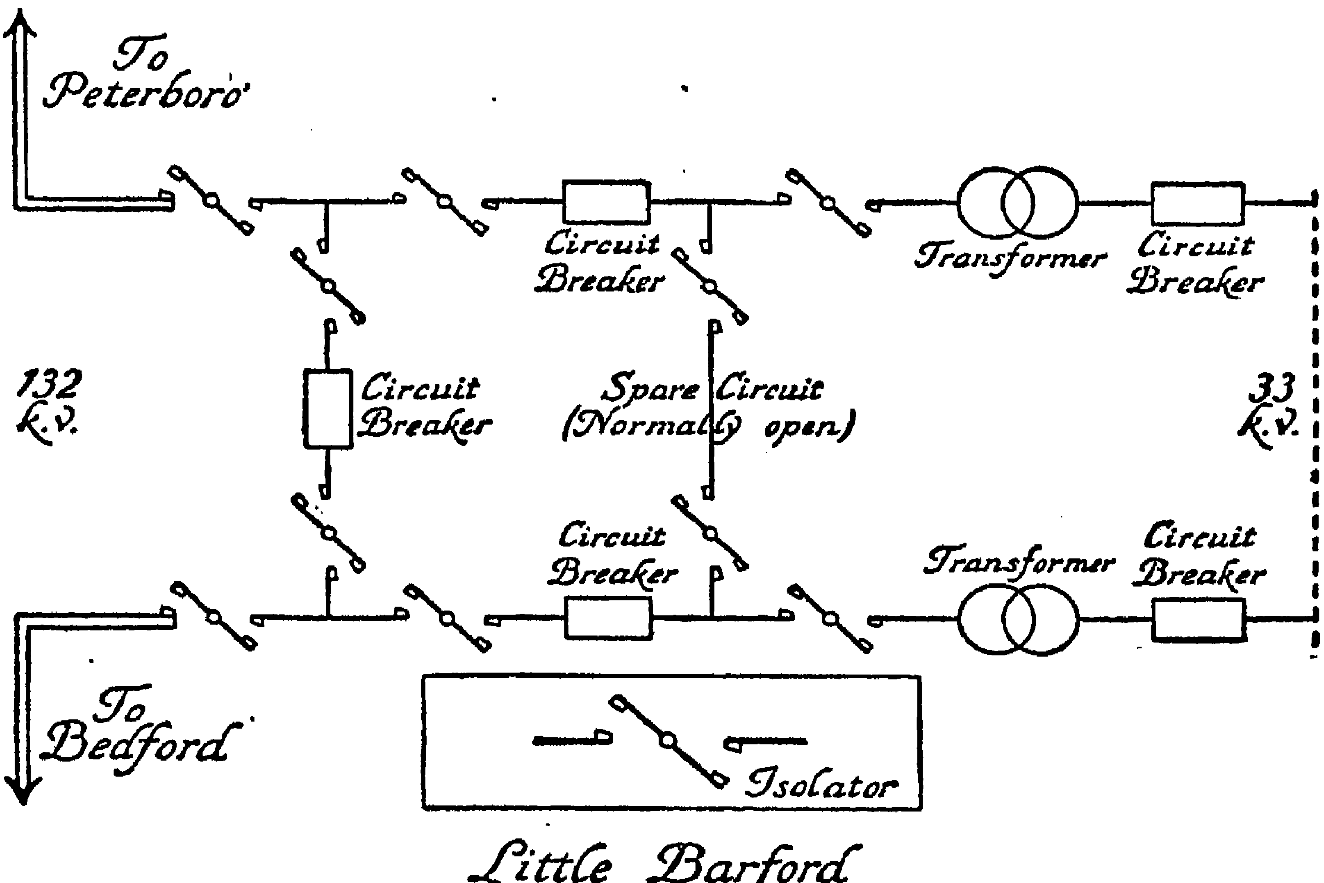


Fig. 94. A plan of the sub-station shown on the opposite page. (*Central Electricity Board.*)

three-phase supply as a single line throughout in order to make the diagram easier to follow. The 'isolators' are arms which swing round, joining lines together when they are closed and disconnecting them when open. They are only used to disconnect the lines when no current is flowing. The 'circuit breakers' on the other hand are switches which can be used to stop the current and which also are thrown open automatically if the current rises to a dangerously high value. They are

essential for protection. Sometimes there is a 'flash-over' on the transmission lines. One cause of this is fog, which deposits a conducting film of moisture on the insulators so that a discharge starts between the cables followed by a great blaze which effectively short-circuits them. This would spell disaster to generators and transformers if they were not protected by the circuit breakers, which immediately 'trip' and cut off the current. In Fig. 94*b*, all the isolators are closed in normal working except those on the spare circuit. If anything happens to the Peterboro' line the two circuit breakers nearest to it immediately break contact. One of the transformers still gets energy from the Bedford line, so the local supply is not cut off. If a short circuit occurs in the local supply, the circuit breakers between it and the transformers are tripped. In that case all the lights in the neighbourhood go out (you will know how this sometimes happens) but the transformers and grid are protected, and the supply will come on again directly the trouble is put right. Everything is safeguarded as far as possible.

Any part of the system which has to be put right is of course first cut off by the isolators so as to make it safe to approach it. If you realize the need for all this gear, and for the wide separation and insulation of the high tension wires from each other, you will see why even a simple sub-station like this is so large.

The circuit breakers are immense affairs. At first sight it would seem that a switch is the simplest thing possible. If two pieces of metal touch, the current flows; if they are separated it cannot flow. However, even in our house supply a switch has quite a complicated mechanism (Fig. 95). If you unscrew the cover,

and work the light switch, you will see that when it is turned off the contact comes out with a snap, being jerked out by a powerful spring. If the contacts were separated slowly, there would be an arc which might melt the metalwork of the switch. If such precautions

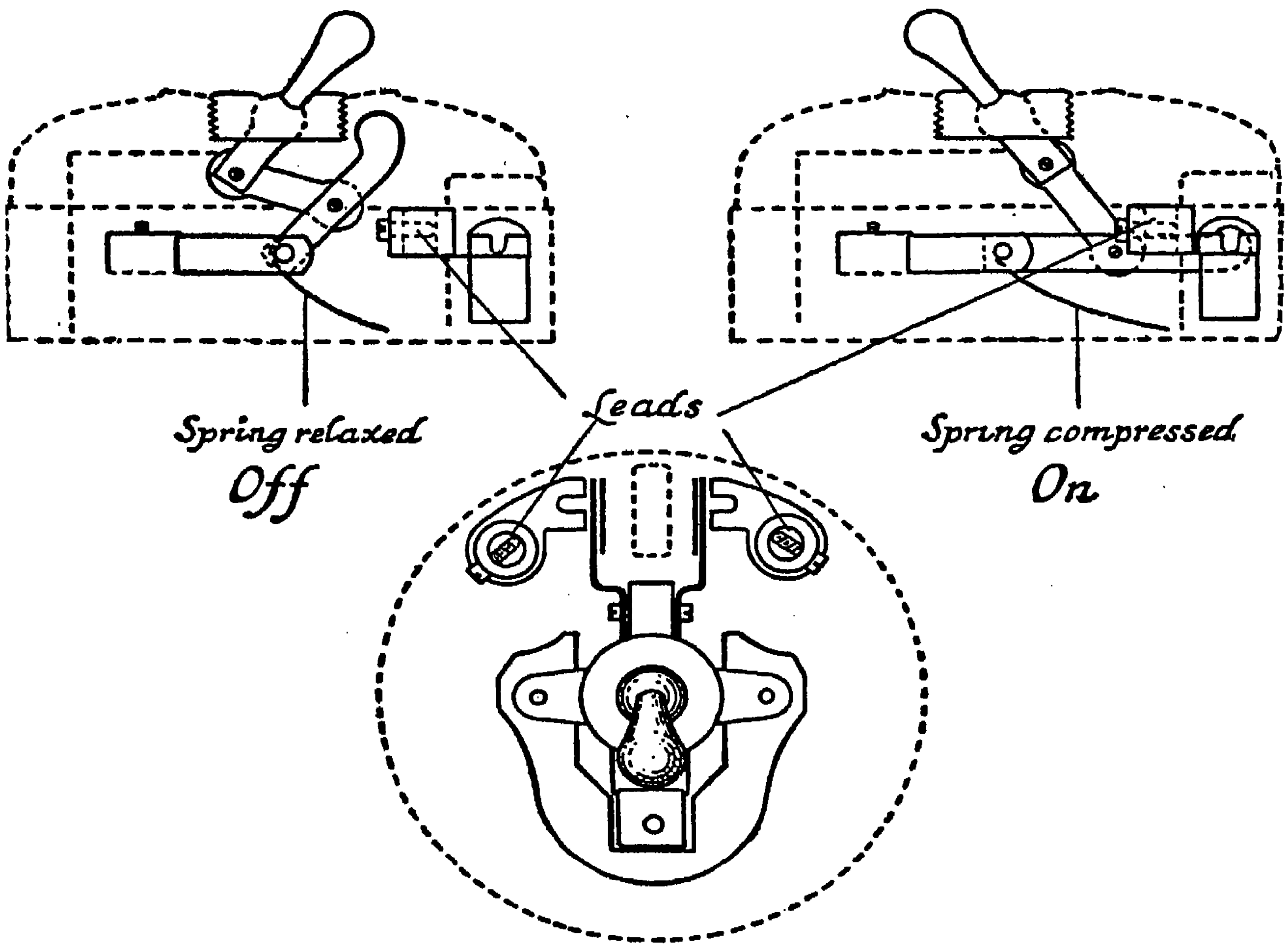


Fig. 95. A domestic switch.

have to be taken for 230 volts, you can imagine what an engineering problem a switch for 132,000 volts presents. Contact is made by metal plungers which fit into holes. An electro-magnet beside the switch controls a powerful spring, and when the switch is tripped the spring pulls the contacts out with terrific force. Several of the circuit breakers can be seen in Fig. 94, Plate 26. The cylindrical tanks contain the oil in which the switches work, and the wires lead into

the tank through long porcelain horns so as to be safely insulated.

The fuses in a house supply have the same protective duty on a small scale as the circuit breakers. The ordinary fuse is a piece of wire either of an alloy which melts easily or of thin copper. There is generally a pair of fuses in the fuse-box for each group of three or four rooms in the house. If the wires to the lamps are allowed to touch so that there is a short, so large a current runs through the fuse that the wire melts, and any damage from the excessive current is prevented.

The towers which carry the transmission lines (Fig. 96, Plate 27) are so well known that I will only draw your attention to the *three* conductors (or six on a double circuit) for the three-phase current, the earthing conductor attached to the top of the tower, and the strings of insulators. The conductors are about $\frac{3}{4}$ inch in diameter, and are made of strands of aluminium to give a high conductivity with a core of steel strands for strength.

Descriptions such as these are very dull affairs unless one also looks at the actual machinery. However, you will find a visit to a power station far more interesting if you understand the way it works, and I hope that the account I have given here will enable you to talk as a brother expert to the engineer who is taking you round, and to plunge into technical discussions with him as to how such vast amounts of power are safely handled.

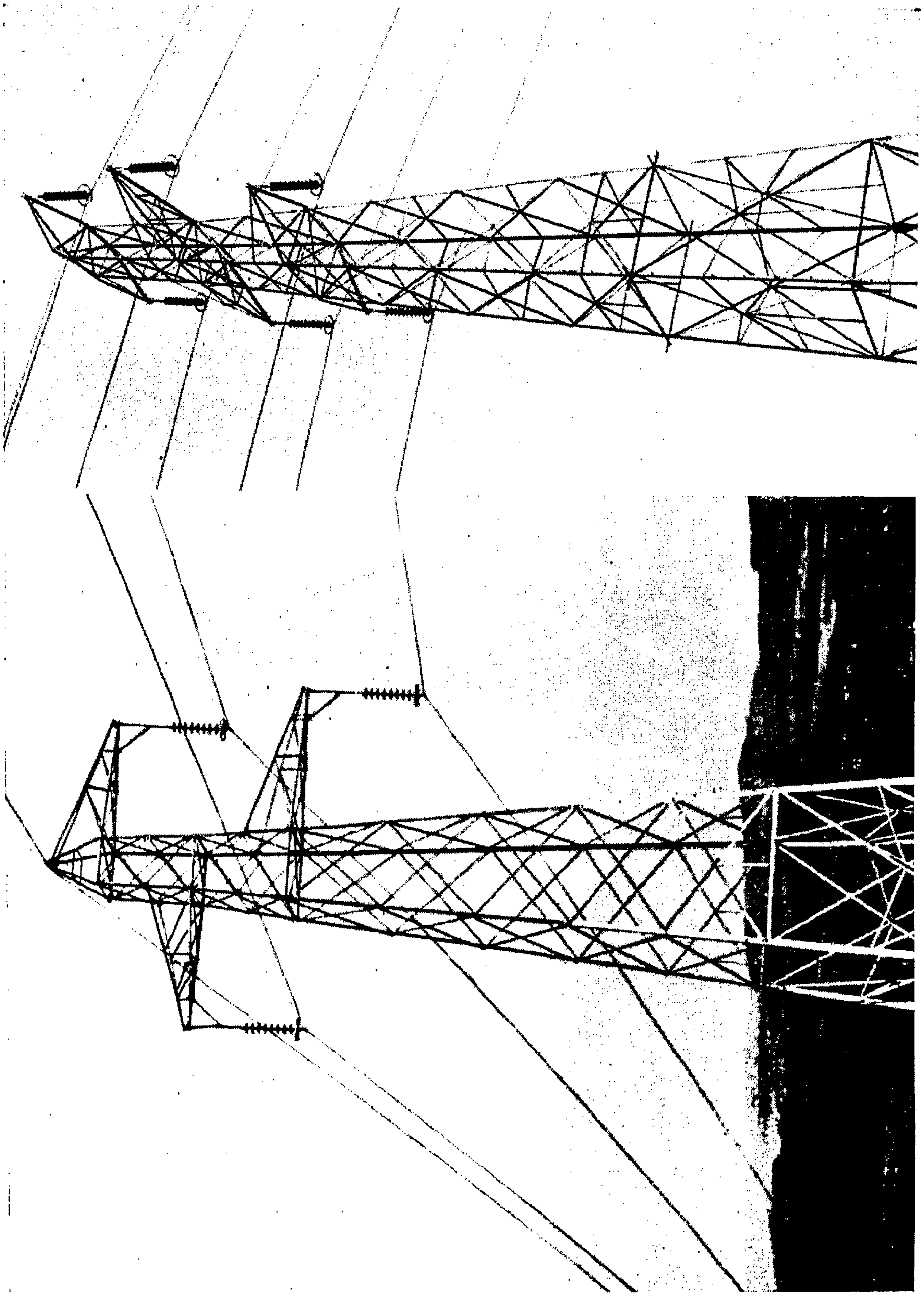


Fig. 96. Towers carrying 132,000 volt transmission lines of the Grid (*Central Electricity Board*)

PLATE 28

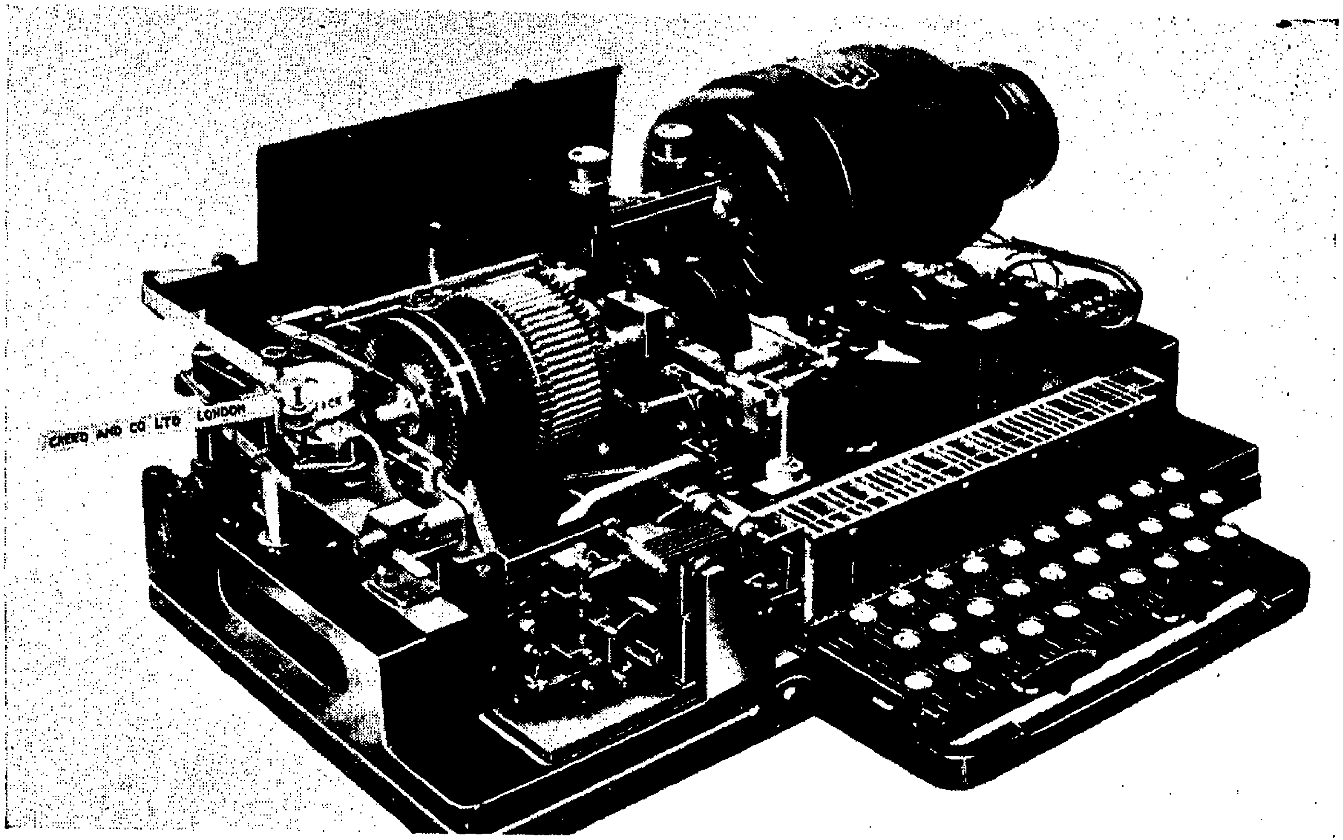


Fig. 102. The Creed teleprinter with its case removed (*Post Office Engineering Department*)

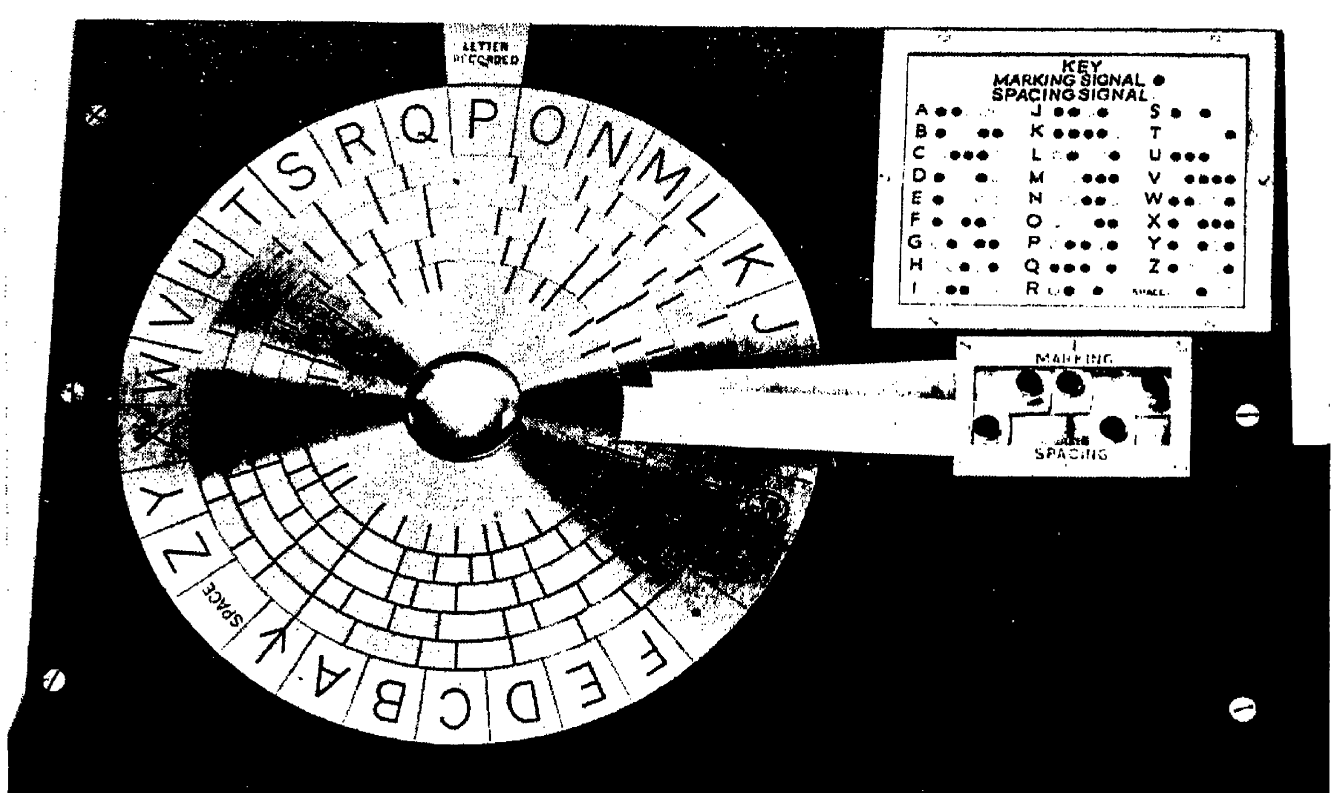


Fig. 103. Model illustrating principle of Creed teleprinter (*Post Office Engineering Department, Research Branch*)

CHAPTER V

TELEGRAPHS AND TELEPHONES

TELEGRAPHS

I. THE DEVELOPMENT OF TELEGRAPHY

At the beginning of the last chapter, I mentioned the two broad divisions of the use of the electrical current, to convey power and to convey messages. It is difficult to say which has had the greater effect in changing our lives and habits.

Before the coming of the telegraph, a message had either to be conveyed by entrusting it to someone's memory, who then travelled to the right place and delivered it, like the messenger who appears in Greek plays, or by entrusting it to writing and sending the letter by land or sea. In either case it could only go with the speed with which men travelled. People in different parts of the world were cut off from each other by vast intervals of time. One part of the world responded in an extremely sluggish way to what was happening in another part, because the rate of reaction was fixed by the time taken by news to travel backwards and forwards.

The wires which now link one country to another are doing the same thing for the world as a whole that our nerves do in our bodies. News spreads over the world almost instantaneously, and no big event can take place anywhere without every country becoming

immediately and thrillingly aware of it and rea to it. The development of the telegraph and means of instantaneous electrical communication historical event of infinitely greater importance the rise and fall of empires and wars of conque which so much space is devoted in history books we contrast the different forms of animal life, o the most marked distinctions is that the higher f have a more complicated nervous system for trans ting messages and orders from one part of the boc another than the lower types. We may say by ana that the telegraph has made a higher type of orga tion possible for the whole world. We may even g to say that many of the troubles at the present tim nervous disorders, due to too close a link betv countries before they are prepared for it. Ano factor in providing the link is of course the incre ease of transport, but I can quite believe that historian of the future will consider the developn of instantaneous communication to be equally portant.

The idea of an electric telegraph was simmerin people's minds for nearly a hundred years befo practical form was invented. The earliest prop seems to have been made by one Charles Morriso Renfrew in 1753. The early forms all employed idea of charging a long wire by a frictional mac at one end, and observing the discharge at the ot They were not practical because it is difficult to re an electrical charge at high potential, and the capa of the wires is high. A practical telegraph became possible when Volta invented his pile Oersted discovered the effect of a current on a mag

The use of a current along a wire is the secret of successful telegraphy, which depends upon the enormous difference in conductivity of different materials.

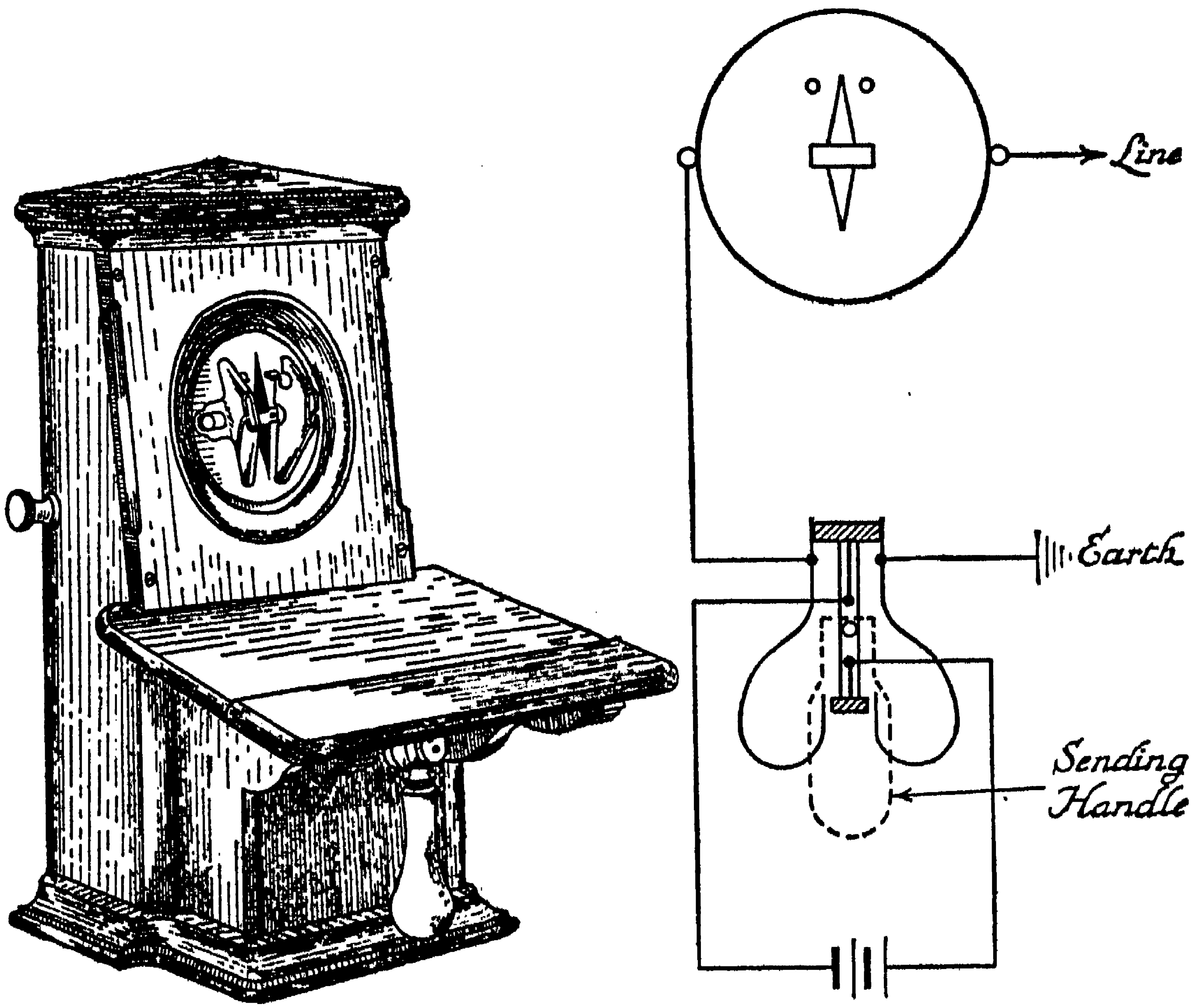


Fig. 97. The needle telegraph. The upper and lower ends of the contact lever, to which the battery leads are connected, are insulated from each other. When the handle is not being used to send messages currents from the distant station flow through the receiver direct to earth.

To realize this we may remember that a current passed into a cable in England prefers to find its outlet in America by running along several thousands of miles of copper conductor, rather than by passing through less than an inch of insulation which is all that separates it from a short-cut back through the sea.

The first current telegraph was the invention of a German called Sömmering. It was an extraordinary affair worthy of the genius of Mr. Heath Robinson, but it had the merit of really working. He had a number of small pots, each with a letter or number on it, containing acidulated water. There was a separate line from the sending station to each pot, ending in an electrode. When a current was sent through the appropriate wire, bubbles of gas in the pot indicated

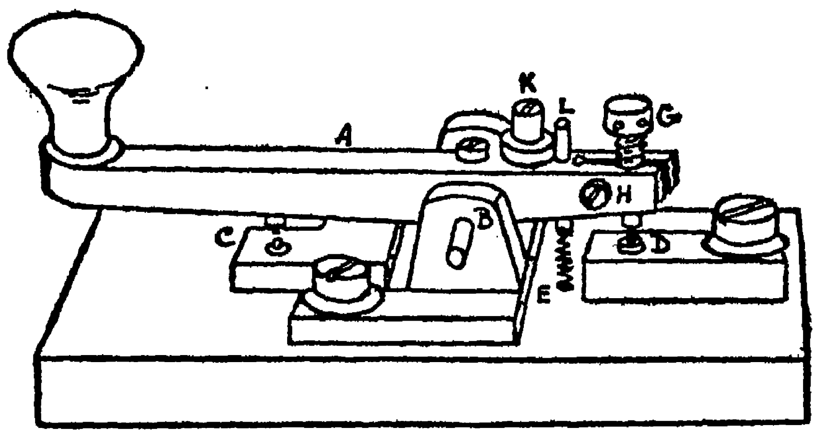


Fig. 98. A Morse key for sending messages by 'dot and dash'

the letter. This telegraph was worked for a distance of about two miles.

Practical telegraphy started with the experiments of Wheatstone and Cooke in this country and Morse in America. The Wheatstone instruments were first used for railway signalling, and one form has been retained on some railways to this day. You may have noticed at railway stations a needle flicking backwards and forwards, hitting two little stops which give out a characteristic 'ting-tang.' A picture of this instrument is shown in Fig. 97. The sending handle transmits currents in one direction or the other along the line when moved right or left, and the current flows round a coil in the receiver and twists a magnetic needle as

in a galvanometer. Dots and dashes of the Morse Code (see below) are indicated by deflections to left and right respectively.

Morse was the first to employ an electromagnet to record the signals, and in the middle of the last century he developed a form of telegraph which is so robust

THE INTERNATIONAL CODE

A	- —	J	- — — —	S	- - -
B	— - - -	K	— - —	T	—
C	— - — -	L	- — - -	U	- - —
D	— - -	M	— —	V	- - - —
E	-	N	— -	W	- — —
F	- - — -	O	— — —	X	— - - —
G	— — -	P	- — — -	Y	— - — —
H	- - - -	Q	— — - —	Z	— — - -
I	- -	R	- — -		

NUMERALS

1	- — — — —	6	— - - - -
2	- - — — —	7	— — - - -
3	- - - — —	8	— — — - -
4	- - - - —	9	— — — — -
5	- - - - -	0	— — — — —

Note.—The 'International Code' is the earlier Morse Code modified so as to make it more suitable for trans-oceanic cable telegraphy.

Fig. 99

and practical that its use has been universal almost up to the present day. The signals are sent along the line by means of *dots and dashes*, a dot being a short impulse of current, and a dash, one which lasts about three times as long. The operator sends them by means of the key shown in Fig. 98, which makes contact at C when it is depressed and breaks it when pulled back by the spring E.

The code is shown in Fig. 99; it has been adopted

for all sorts of signalling purposes because of its convenience, and it is probably familiar to many of my readers. It is based on the principle of giving the simplest signals to the most frequently used letters, E and T having priority over all the others.

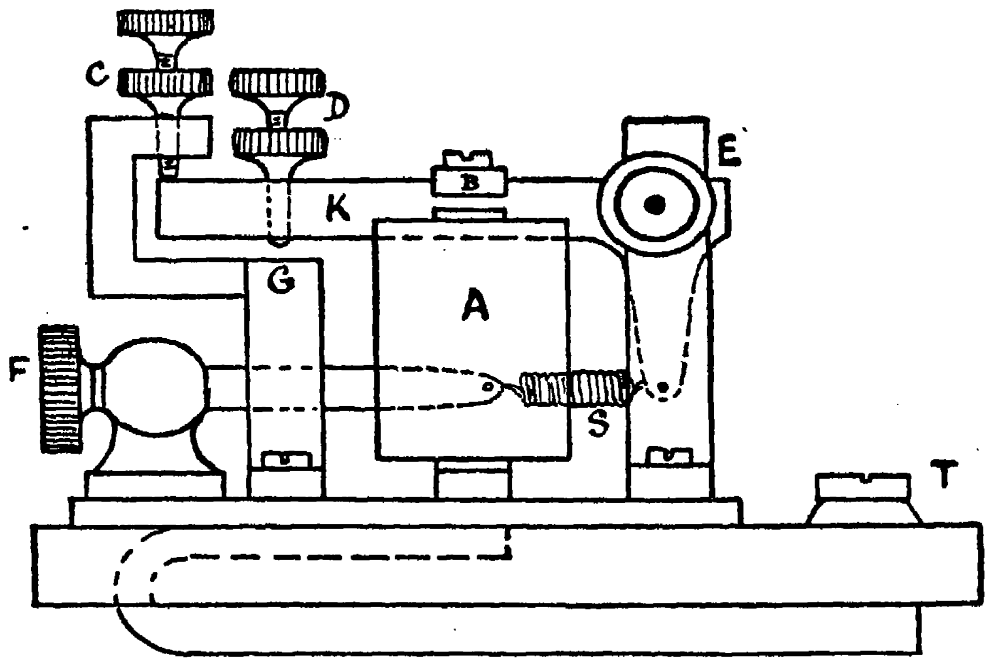


Fig. 100. The Morse Sounder. The screws C, D are used to adjust the up and down movement of the arm K.

A Morse 'sounder' is shown in Fig. 100. The current at the receiving end flows through an electromagnet A, which attracts a soft iron armature B on a lever K pivoted at E. The message is generally read by an operator who listens to the clicks as the armature is attracted and released. In other forms of instrument, the dots and dashes are recorded on a moving paper tape by an inked wheel attached to the arm of the receiver.

It is inconvenient to send the powerful current required to work the recorder over long distances because of the resistance of the lines. A relay is therefore used. A relay is like a delicate recorder in which the armature is pulled down by an electromagnet

with many turns of fine wire. When pulled down by a weak current it makes a contact, and a powerful local battery then sends its current through this contact to the sounder or receiving instrument. A relay is a general name for an instrument in which a feeble current opens or closes a circuit and so governs a powerful current.

This system of telegraphy has held its own for nearly

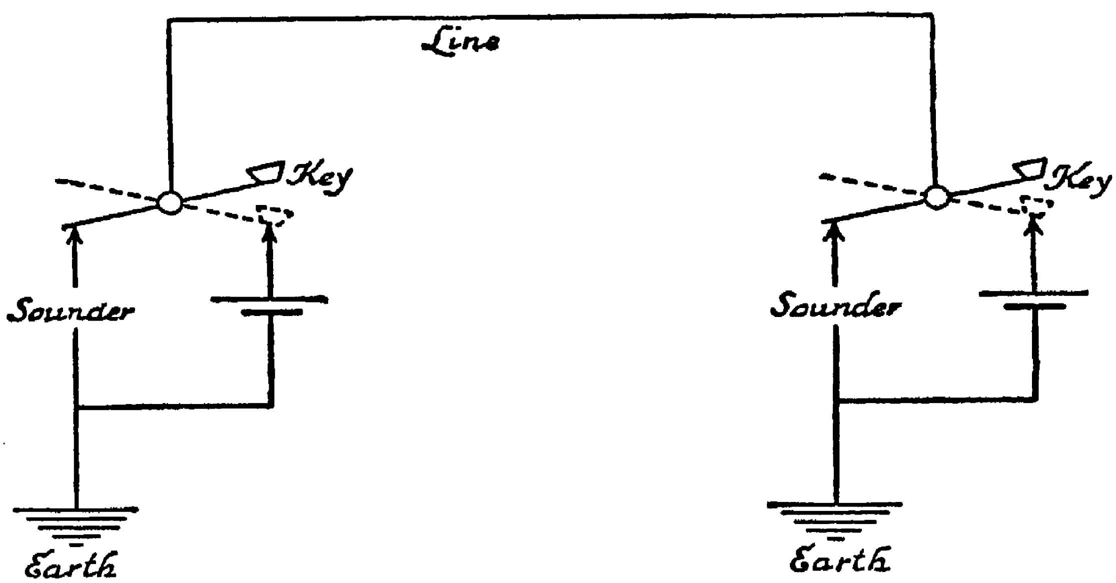


Fig. 101. An arrangement of a circuit so that messages can be sent in either direction, by a single line and 'earth' return.

a hundred years. Improvements have been mainly directed towards increasing the speed of working and reducing the number of lines. For instance, a great invention of early days was the 'earth return.' Instead of having two lines from sending station to recording station, one lead at each end was connected to a large plate sunk in the ground, so that the world itself formed one conductor and only one line was required between the stations. This is equivalent to using the whole world as a return wire, and as long as good contact is made by the earthing plate, its resistance is negligible. Fig. 101 shows a circuit with an

earth return and which is so arranged that a message can be sent in either direction.

Then various interesting schemes for using one wire for simultaneous messages in each direction were developed, which it would take too long to describe here. In certain systems automatic sending was used in order that each line might work up to full capacity. The message was tapped out by an operator on an instrument which perforated a paper tape instead of sending currents. This tape was then fed through the sending apparatus at a much faster rate. As each perforation passes two contacts they touch and a current is sent. An operator can only send about 30 words per minute, but the telegraph itself can transmit dots and dashes at the rate of 600 words a minute. A number of operators could therefore be kept busy putting messages on tapes, which were rushed through the instruments working on a single line, and the record cut up and written out by several operators at the far end.

Alterations in a telegraph system are not easy to make, because operators who have worked with it for years become very efficient through practice, and it is extremely difficult for them to unlearn one code of signals and learn another. This may be one reason why the Morse system has held its own with no serious alterations for so long a time. It has at last been given up in this country. Most of us can remember hearing the tapping of the key in the background when we were in a post office, but that familiar sound has gone, and telegrams are now sent by entirely different methods.

2. TELEPRINTERS

If you go into the room in a large central post office from which telegrams are being dispatched, you will see a number of machines which look like complicated typewriters (Fig. 102, Plate 28). There is a keyboard with letters and numbers on the keys. When a form on which a telegram has been written is handed to the operator, she proceeds to type it as if it were a letter. Her machine, which we will suppose is in Leeds, is connected by a line to a similar machine in London. As she taps the keys in Leeds, electrical signals are sent along the line which print her message on a tape coming out of the London machine, and similarly any message typed in London is printed at Leeds. You can see the tape on which the message is being typed coming round a roller and issuing out on the left-hand side of the machine. When a message is being received the words are printed in a continuous row on the tape. The operator tears off the length of tape with the address and gums it on top of a form, then tears off the message in appropriate lengths and sticks them beneath. You are probably familiar with the look of a telegram coming from a big office, with the slips of paper gummed on to it. These machines are called *Teleprinters* and are installed in all large post offices.

If the place to which the telegram is addressed is near the central office, the telegram is delivered by messenger. If it is in an outlying district, the form is sent to another room from which it is *telephoned* to the post office nearest its destination and sent by messenger from there. When we get telegrams in writing, it is because they have been telephoned on to a local

office which has not got a teleprinter. A third plan, which is becoming increasingly common, is to telephone the teleprinter message to subscribers connected to the exchange, and send a confirmation later. The teleprinter and telephone have replaced the 'dot and dash.'

Different types of teleprinter are used in different countries. In England we use the Creed instrument. It is too complicated to describe in detail, but I can perhaps illustrate the general principles of this and other similar instruments.

We want to arrange that, when we press the key marked A on the sending instrument, an A is printed on the tape by the receiving instrument. If we were allowed a circuit for every letter of the alphabet (and for all numbers and other signs) it would be easy to cause a current along the appropriate wire to work a key on a typewriter by means of an electromagnet, but this would involve so many lines that it is out of the question. The teleprinter actually works with a single circuit. To make it simpler to understand, however, I will suppose in the first place that five circuits are at our disposal, and show how signals corresponding to all the letters could be sent over five wires; we shall see later how one circuit is made to act like five.

The model in Fig. 103 (Plate 28)[1] illustrates the principle of the method. You will see five inner discs of metal, each of which has an arm stretching out to the right. The discs are pivoted at their centres, and

[1] The original version of this model was constructed for the Christmas lectures; the one shown in the illustration is a finished form built by the Post Office Engineering Department at Dollis Hill.

can be rotated over a small angle by the arms. A black button attached to each arm shows whether it has been moved up or down. Each arm is moved by an electrical current sent along one of the five circuits. In the present case, the code signal for the letter P has been sent and has moved up arms II, III, and V, leaving I and IV down, because currents have been sent along circuits II, III, and V by the transmitting instrument. There are five bars under the keys of the transmitting instrument, and when the key P is pressed it touches the second, third, and fifth bar and sends currents to the corresponding circuits.

The discs, which are called 'combs,' have a number of slots cut in them, represented by lines in the figure. When the arms II, III and V move up, five slots come into line at a certain place which you will see in the figure. The outer circle has the letters of the alphabet printed around its rim, and also an arrow representing a catch. The outer circle is rotated by a motor and clutch until the catch, which lies over all five discs, finds a place where five slots are in a row. The catch then falls down, stops the disc rotating further, and a hammer is released which hits the letter at the top and prints it on the tape. You will see the letter P has come under the hammer (denoted by 'letter recorded' in the figure) when the arrow representing the catch has come opposite the five slots in a row. The arms then fall back into place ready for the next letter.

Suppose the letter A is now to be sent. The first two arms move up and the others remain down. The slots come into line at another place, the arrow rotates until it comes opposite them, and A will be found to

be in the recording position. The complete code is shown in Fig. 104.

It is rather hard to believe that five movements can represent the 26 letters of the alphabet, but actually they are more than sufficient. Since there are five

Letters	Figures	UNITS					Letters	Figures	UNITS				
		I	II	III	IV	V			I	II	III	IV	V
A	:	●	●	○	○	○	Q	1	●	●	●	○	●
B	?	●	○	○	●	●	R	4	○	●	○	●	○
C	(	○	●	●	●	○	S	'	●	○	●	○	○
D	2	●	○	○	●	○	T	5	○	○	○	○	●
E	3	●	○	○	○	○	U	7	●	●	●	○	○
F	1/	●	○	●	●	○	V	)	○	●	●	●	●
G	3/	○	●	○	●	●	W	2	●	●	○	○	●
H	5/	○	○	●	○	●	X	£	●	○	●	●	●
I	8	○	●	●	○	○	Y	6	●	○	●	○	●
J	7/	●	●	○	●	○	Z	.	●	○	○	○	●
K	9/	●	●	●	●	○	/	/	○	●	○	○	○
L		○	●	○	○	●	*	*	●	●	●	●	●
M	'	○	○	●	●	●	÷	=	○	○	○	●	○
N	—	○	○	●	●	○		+	○	●	○	○	●
O	9	○	○	○	●	●	Letter Space		○	○	●	○	○
P	0	○	●	●	○	●	Figure Space		●	●	○	●	●

Fig. 104. The Teleprinter Code. (*Post Office.*)

levers, each of which may be either up or down, there are $2 \times 2 \times 2 \times 2 \times 2 = 32$ combinations. To convince yourself that the slots only come into line at one place at a time, I would warmly recommend you to make up the model for yourself. It is quite easy to construct and rather fascinating to play with. All one needs is some thin cardboard for the discs and a piece of wood on which to fix them. Fig. 103 will be a

sufficient guide for the construction. One first of all cuts out the large outer circle and divides its rim into 30 equal parts by marking 12° intervals with a protractor. The letters are written in these spaces in the order shown, leaving two places blank between G and F because it will be found that when these spaces are under the 'hammer' the arrow will come under the arms and be invisible, so we cannot use them. 'Space' is used to separate one word from the next. The inner discs are now cut out, the arm on each successive one being a bit shorter than the last, so that when they are mounted on the board all their ends can all be seen. A tack or drawing-pin fastens the discs to the board, the smallest being uppermost. Two pins limit the arms to a movement of about 10°, or slightly less than one space on the outer circle. We mark 'letter recorded' at the top and are now ready to mark out the slots.

At first sight it would seem a troublesome business to get these in their right places, but nothing could be simpler. To mark the slots for P, for instance, turn the outer circle till P is under the hammer, set the arms to the code for P, and then with a ruler draw a line on the five inner discs from centre to arrow. Repeat this for each letter and the model is made. You can easily convince yourself that only one row of slots come into line for each letter.

I have simplified the description of the apparatus very much. In the actual instrument the combs are of the same diameter, but it is easier to see the slots come into line if we make them progressively smaller in the model. There are actually seven signals, not five, the first and the seventh being used for starting

and stopping the printing mechanism. Finally, there is a very ingenious arrangement by which the marking signals are sent along a single circuit. The motors at each end are turning at about the same rate, and when the first signal in each set of seven comes along, rotating switches at each end are thrown in by clutches, and connect the first bar under the transmitting keys to the first receiving lever, then the second bar to the second lever, and so on, so that really the marking currents follow one after the other. The seventh signal disengages the printing mechanism and brings it to rest ready for the reception of the next letter. Everything takes place so quickly that the operator can work the keys just as if it were an ordinary typewriter.

Other types of instrument are used in other countries, but I have described this instrument in some detail because it is an example of the trend of modern practice. It shows how we can send a typewritten message along a single circuit. It pays to have a complicated apparatus if we can economize in circuits. Actually, the telegraph system is now worked by what is termed the voice-frequency method, which permits eighteen separate messages to be sent simultaneously over a single circuit. Alternating currents of eighteen different frequencies are employed, one for each sending instrument, and these frequencies are separated out by 'filters' at the far end and distributed to the receiving instruments.

3. TELEGRAPH LINES

The interesting thing about telegraph lines is that nowadays separate circuits are not provided for this purpose, they are stolen from the telephone circuits.

Fig. 105*a* shows how this is effected without 'interference,' i.e. without clicks being heard in the telephone

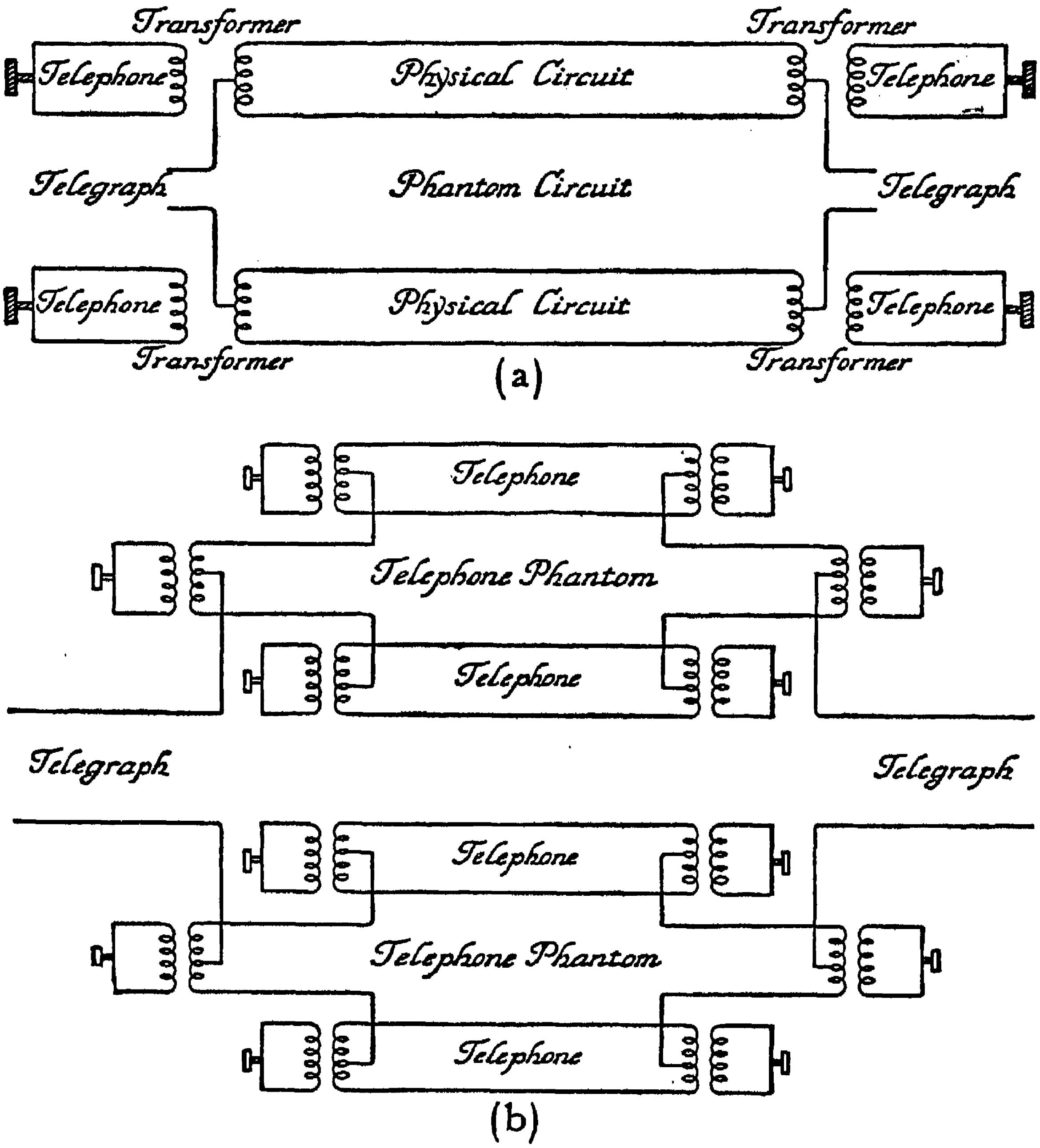


Fig. 105. Phantom Circuits.
(*a*) A combination of two telephone circuits to give a telegraph circuit.
(*b*) Four actual circuits are made to provide six telephone circuits and a telegraph circuit.

receivers due to the working of the telegraph. To understand the circuit, it must be remembered that in telephony the microphone produces variations of electrical current, which can therefore be handed on by a

transformer (see page 157). There are two telephone circuits in the figure, the transformers and telephone being indicated in a conventional way. You will notice that the current sent by the telegraph runs to the centre of a transformer-winding where it splits into two and runs equally along both wires of a telephone circuit. It therefore has no effect on either telephone since the currents in the two halves of the transformer-winding just cut out each other's effects. We have gained a 'phantom' telegraph circuit without spoiling the telephone circuits. Fig. 105*b* shows a sad case of overworking circuits. I think you will be able to follow it, after the explanation I have given of the simpler case. Four circuits are being made to serve six telephones and a telegraph. Accurate balancing of the circuits has to be done by the Post Office engineers to make such schemes work.

4. SUBMARINE CABLES

Though sending telegraphic signals along a cable under the sea is in principle the same as sending them by overhead wire or land cable, there are certain special features. The long cable has a high resistance, and as it is not safe to transmit at too high a voltage (about 60 volts is usual) the currents at the far end of the cable are very feeble. The Morse code is used, but a current in one direction is sent for 'dot' and a reverse current for 'dash.'

The currents are registered at the far end of the cable by an instrument called a 'siphon recorder,' shown in Fig. 106. They pass through a little coil of wire suspended in a magnetic field, much as in the moving-coil ammeter described in Chapter III, and the coil

twists one way or the other according to the direction of the current. The coil is shown separately in Fig. 106*b*. Attached to it at the points UV are two silk reins which go to a light mica plate Z, which is suspended on a silk fibre ST (Fig. 106*a*), so that when the coil moves it waggles the plate about the axis ST. A thin glass tube JKW is attached to the mica plate. It dips into an inkpot at J, and the ink writes at W on a tape dd, which is running along. Since the inkpot is higher than W, the ink tends to 'siphon over.' If the end of the siphon rested the whole time on the paper, the coil would not be strong enough to move it against the friction, and also the ink would not run out because the tube has to be so very fine. This difficulty is overcome by attaching the siphon by the silk thread XY to the electromagnetic trembler P, which keeps the tip of the siphon dancing on and off the paper. Each time it touches it, a little ink dot is jerked out, and, of course, when it is not touching, the coil can move it. The current is therefore registered on the paper as a wavy line of dots.

Fig. 107 shows (A) the actual currents sent by the transmitting station, and (B) the same currents registered by the recorder at the far end of the cable. A dip below the line is a dash, and a peak above the line is a dot (compare with the Morse code in Fig. 99). In the lower record you will see the dots made by the siphon. What I wish you especially to notice is the way the signals tend to get jumbled together and blurred, for this illustrates the most important difficulty which has to be overcome in submarine signalling.

The signals tend to smooth out like this because of the electrical capacity of the cable. It has a central

copper conductor, surrounded by guttapercha for insulation, and 'armoured' outside by steel wire for protection. The long cable as it lies on the sea bottom

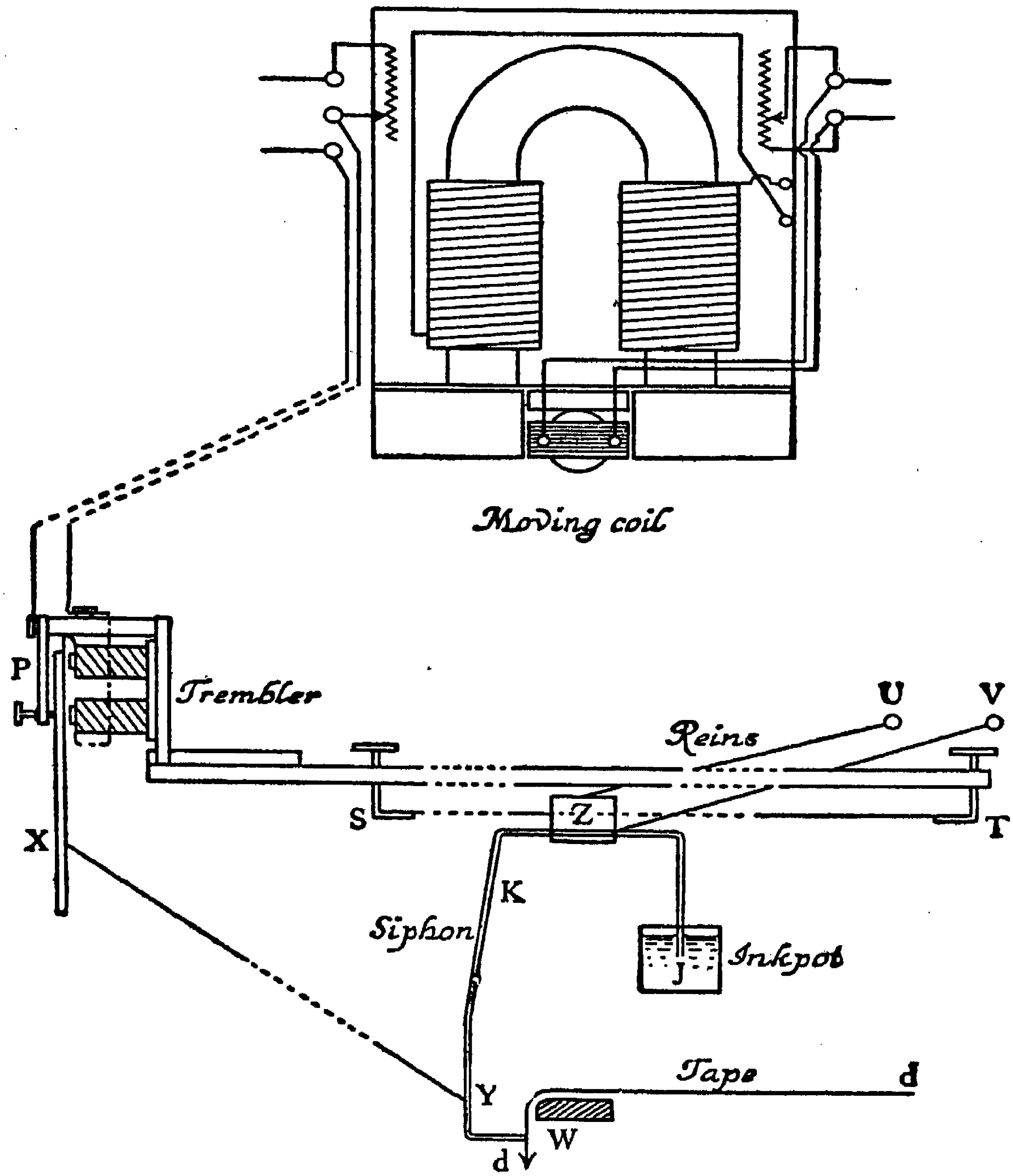


Fig. 106*a*. The Siphon Recorder. (*Giuli's Submarine Telegraphy.*)

has an immense capacity. When a current is sent into it at the transmitting station, it charges the cable, and it must discharge again before a current in the reverse direction can reach the recorder. In consequence the

signals at the far end lose their sharpness. As an analogy, we may think of a channel with a number of pools connected to it, such as one sees on a rocky sea-shore. When the wash of a wave flows into the seaward end of the channel it fills the pools as it advances, and as the wave recedes the pools all drain back into the channel. As a result, the rise and fall of the water at

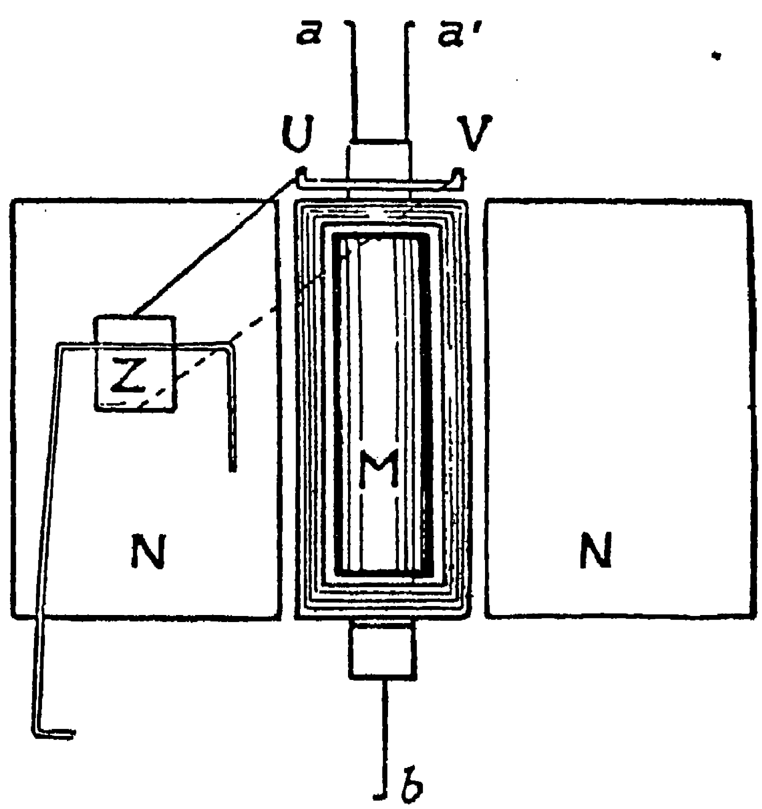


Fig. 106*b*. Coil of Siphon Recorder.

the far end of the channel is much less than at the mouth. The capacity of the cable acts in the same way as the pools in our analogy, and we can see why the sharply defined currents sent by the transmitting station get rounded off when they reach the recorder.

The speed with which signals can be sent is limited by this effect. If they are sent very deliberately, the current has time to charge up the cable and flow out at the far end, but if they are sent too rapidly the signals

run together. You and I would probably have considerable difficulty in untangling the record shown in Fig. 107, though it is plain to an expert. Since the cable is a very costly affair it has to be used to its full capacity, and the signals are sent as fast as is consistent with their clearness when recorded.

A revolution in the construction of cables has been made by wrapping round the copper conductor a tape made of a nickel-iron alloy called permalloy. This

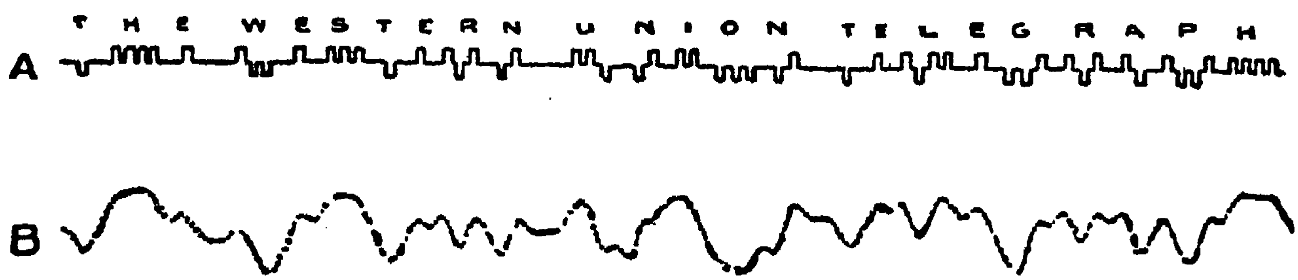


Fig. 107A. A message sent out by the transmitting station, dots being represented by a current in one direction and dashes by a current in the other direction.

Fig. 107B. The same message as written by the siphon recorder at the receiving station.

alloy has the property of being extremely easily magnetized by a weak magnetic field such as that due to the feeble currents in the cable. It would take us too far into theory to explain how the magnetic 'loading' produces its effects, but the result is to keep the signals sharp. When an impulse of current is fed into the unloaded cable, its advancing crest is flattened out by charging up the condenser like the wave filling the pools. In the loaded cable the current magnetizes the iron as it goes along, and the induced electromagnetic forces so react that this impulse moves like the 'bore' which runs up some tidal estuaries, with a crisp beginning instead of a sluggish turning of the tide. This makes it possible to increase the working speed ten

times, or in other words one of the new cables is as useful as ten of the old type.

Permalloy was discovered by the Bell Telephone Laboratories in America. The whole story of the improvement of cables is a striking instance of the application of science to industry. The right conditions for sending signals without distortion were worked out mathematically by Heaviside, and a prolonged search for a magnetic alloy which would make it possible to satisfy his conditions led to permalloy and revolutionized this vast industry.

TELEPHONES

5. THE NATURE OF SPEECH

Sound consists of waves travelling through the air at a rate of about 1,100 feet per second. The word 'waves' generally conjures up the image of ripples or undulations running across a surface which is heaving up and down like the sea. In the case of sound, the waves are of another kind. We may make a picture of them by thinking of an engine, shunting a long line of trucks, which gives a short push to the first truck and then stops again. The first truck shoves against the second and compresses the buffer springs. The springs stop the first truck and push on the second one so that it is now the moving one. It hands on its motion to the third truck, coming to rest itself in turn, and so on along the line. One has often seen the motion, accompanied by a clanking of buffers, running down a line of trucks in this way. Now air is both springy like the buffers, as we know when pumping up a tyre, and has

mass, as we realize when a strong wind is buffeting us. If we give the air a sudden push so as to compress it, its springiness sets the neighbouring air moving, and the motion is handed on through the air just like the movement of the shunted trucks. Sound waves travel so rapidly that they appear to reach us instantaneously when coming from a short distance away, as when someone is speaking to us in a room. We can realize that they actually take some time to arrive when the sound comes from a distance. If a steamer a mile away blows its siren, we see the steam issue from it about five seconds before the sound reaches us. The interval between lightning and thunder, or between seeing and hearing the blows of a man chopping or hammering in the distance, are other instances. The rapid velocity of sound is due to the lightness of the air, and its strong resistance to compression and extension, or 'springiness.'

When a sound-wave reaches us, the air moves backwards and forwards along the direction in which the sound is travelling, and also its pressure fluctuates. The rapid alterations of pressure on the ear-drum affect the nerves in the inner ear and give the sensation of sound. The pitch of a note is determined by the number of vibrations of the air per second, i.e. the frequency. The middle C of the piano, for example, has a frequency of 256. Our ears are sensitive over an enormous range both of pitch and intensity. Individuals vary a good deal as regards the range of pitch, but normally the lowest note we can hear makes about fifteen vibrations a second, and the most shrill somewhere between 10,000 and 20,000. People lose their ability to hear the higher notes as they grow older;

a bat's squeak is a good test, because it is in the region of the upper range of audibility. The range between the faintest note we can hear and the loudest note we can stand without its becoming painful is also exceedingly great. In the region of about 500–1,000 vibrations a second, where the range is greatest, the pressure variations in an unpleasantly loud note are about one hundred million times as great as those in a faint note we can just hear.

Our understanding of the way in which speech is produced is largely due to the original work of Helmholtz and more recent researches by Miller, Fletcher, Paget, and other workers in this field. While we are speaking we are making two distinct kinds of sound simultaneously. In the first place we are making a sound by forcing the air through a part of the throat called the larynx, where two membranes stretched by muscles form a narrow slit and vibrate as the air rushes between them. The pitch can be varied by altering the tension of the muscles. This sound by itself is not speech, it is merely the 'tone' of the voice, which rises up and down in the inflection of a spoken sentence, or is held steady in singing. In the second place, we are creating a running accompaniment of rapidly varying notes by altering the shape of the mouth as the main tone issues from it, and this accompaniment represents the vowels and consonants. There is a fundamental difference in the use of vowels and consonants, a simple vowel being a continuous sound, and a consonant a way of leading up to or ending that sound. The tongue divides the mouth into two cavities, one behind the tongue with an opening between the tongue and the roof of the mouth,

and one in front of it with an opening through the lips. The air in a cavity with an opening gives out a characteristic note, as one can tell by blowing across the opening of an empty bottle. The note can be varied by altering the size of the cavity, such as by partially filling the bottle with water, or by altering the size of the opening. The larger the cavity and smaller the opening, the lower is the note. As we speak, the two cavities in the mouth give out two characteristic notes, a lower one and an upper one, and we make the different vowels by altering the pitch of these notes. The lower one ranges from 300 to 900 in frequency, and the upper from 600 to 2,600. If you try whispering a *French* 'a, e, i, o, u' you will soon convince yourself, both that you are altering these resonant cavities in your mouth so as to get different notes, and that the vowels have nothing to do with the noise made by the larynx, because when we are whispering the larynx is not working. English vowels are not pure, that is why French ones are preferable. The consonants are ways of starting and stopping the vowels abruptly or gradually or of prefacing them by short grace notes and other musical ornaments.[1]

The point I wish to make is that speech has no especial mysterious quality. Each word is a tiny tune, and we recognize it in the same way that we recognize 'God Save the King.' This tune is played by the mouth and also partly by the nose, as we realize when we have

[1] An interesting example of probably unconscious recognition of the definite frequencies associated with vowels is to be found in books on wild birds. Their songs or calls are represented by *words*. The song of the thrush, for instance, is compared to the words 'Go it. Go it. Stick to it. Stick to it. You'll do it. You'li do it.' If one whispers these words, or the names Cuckoo, Curlew, Peewit, one is forced to recognize their appropriateness.

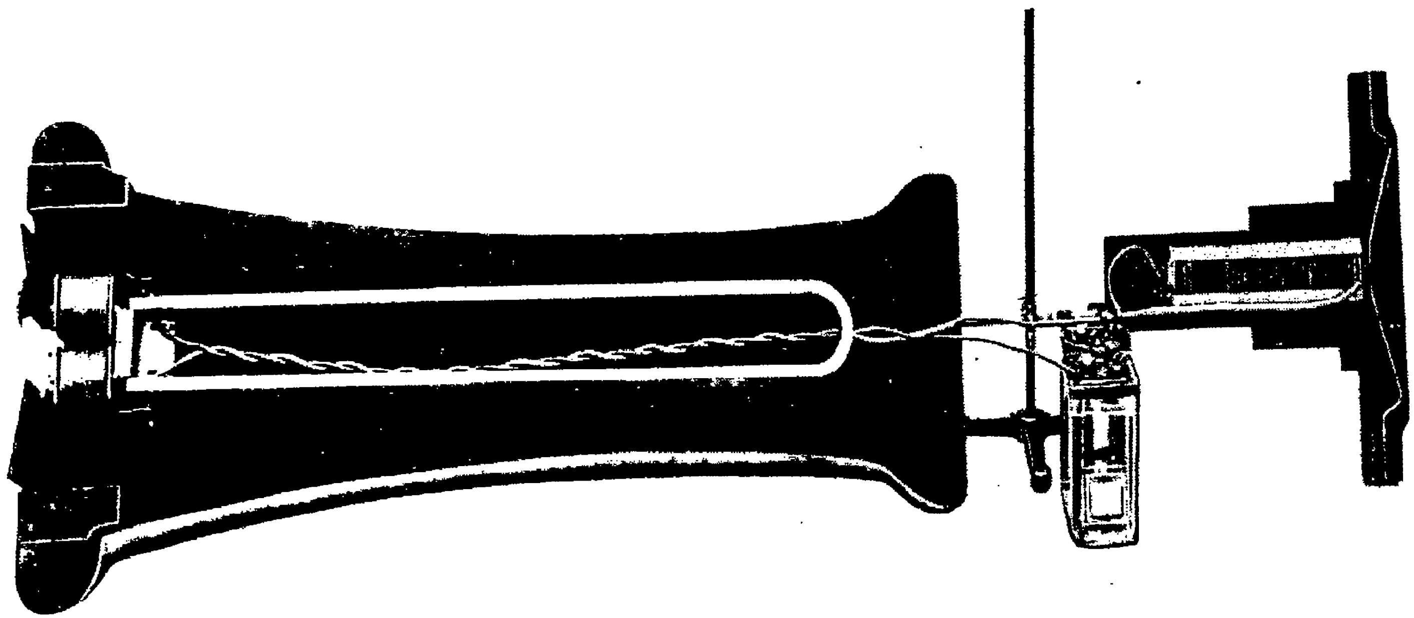


Fig. 108. Model illustrating the principles of a telephone transmitter and receiver

Fig. 120*b*. A 'Cable Tree.' The successive layers of telephone wires inside the cable (1,100 pairs) have been laid bare (*Post Office Engineering Department*)

[*p* 216

Fig. 111. A manual exchange. The inset shows a connection between two subscribers being made (*Post Office Engineering Department*)

a bad cold in the head. It must be distinguished from the sound produced in the larynx which rises and falls or gives the melody of a song. When we remark, 'It wasn't what he said, it was the nasty way he said it,' we are unconsciously distinguishing speech on the one hand from the larynx noise on the other hand, which latter is largely responsible for conveying emotion apart from words. You must picture these two tunes going on independently, the one being heard by itself in singing without words, and the other in whispering.

The little tune which makes up speech is played in a much higher key than that of the larynx, and this has a most important practical bearing in telephony. Further, just as we can recognize 'God Save the King,' whether played on an organ or a banjo, so we can recognize a word as long as the right notes are there, even when their relative intensity is distorted to an extraordinary extent. The ear has an amazing power of adjusting itself to circumstances. The problem of telephony consists in transmitting the speech-tune from one place to another. A telephone may, and actually does, distort the sound greatly, but it must transmit the main notes of speech so that words may be recognized clearly.

6. TELEPHONE TRANSMITTERS AND RECEIVERS

The principle of telephony is extremely simple. Fig. 108 (Plate 29) shows a large model transmitter and receiver made for the Christmas lectures which illustrates how the sounds are conveyed.

The transmitter, or microphone, into which we speak when telephoning, has a flexible plate or diaphragm

which is set in vibration by the sound waves. Behind the diaphragm are a number of carbon granules (represented by the carbon blocks in the model). When the diaphragm moves in, these granules are pressed more tightly together and form a better contact; when it moves out the contact is lighter. A battery drives a current through the granules, which becomes stronger as the diaphragm moves in and weaker as it moves out. The microphone thus turns variations of air pressure into variations of electrical current.

In the receiver, this current is passed round the coil of an electromagnet, placed behind a thin diaphragm made of iron. The diaphragm is pulled in when the current is stronger and flies back when it is weaker. It therefore vibrates backwards and forwards in sympathy with the diaphragm of the transmitter, and so sets up sound-waves in the air which resemble those received by the transmitter. The large model has a light lever attached to the iron plate in the receiver, and by pressing with one's finger on the transmitter, the lever can be made to waggle backwards and forwards.

Fig. 109 gives diagrams of an actual transmitter and receiver. The chamber of the transmitter is full of small carbon granules, so that the two carbon electrodes between which the current flows are completely bathed in them. This arrangement has been found to prevent the granules getting wedged tight between the electrodes, a trouble which one used to cure in former times by giving the transmitter a hearty knock when one could not be heard well. Many experiments have been tried to find whether there are better substances for microphones than carbon, but with no success.

Carbon appears to be far the best. The receiver has its two pole pieces of soft iron fastened to the ends of a permanent magnet. When the current is running in one direction in the coils round the pole pieces it increases the magnetic field, and when running in the

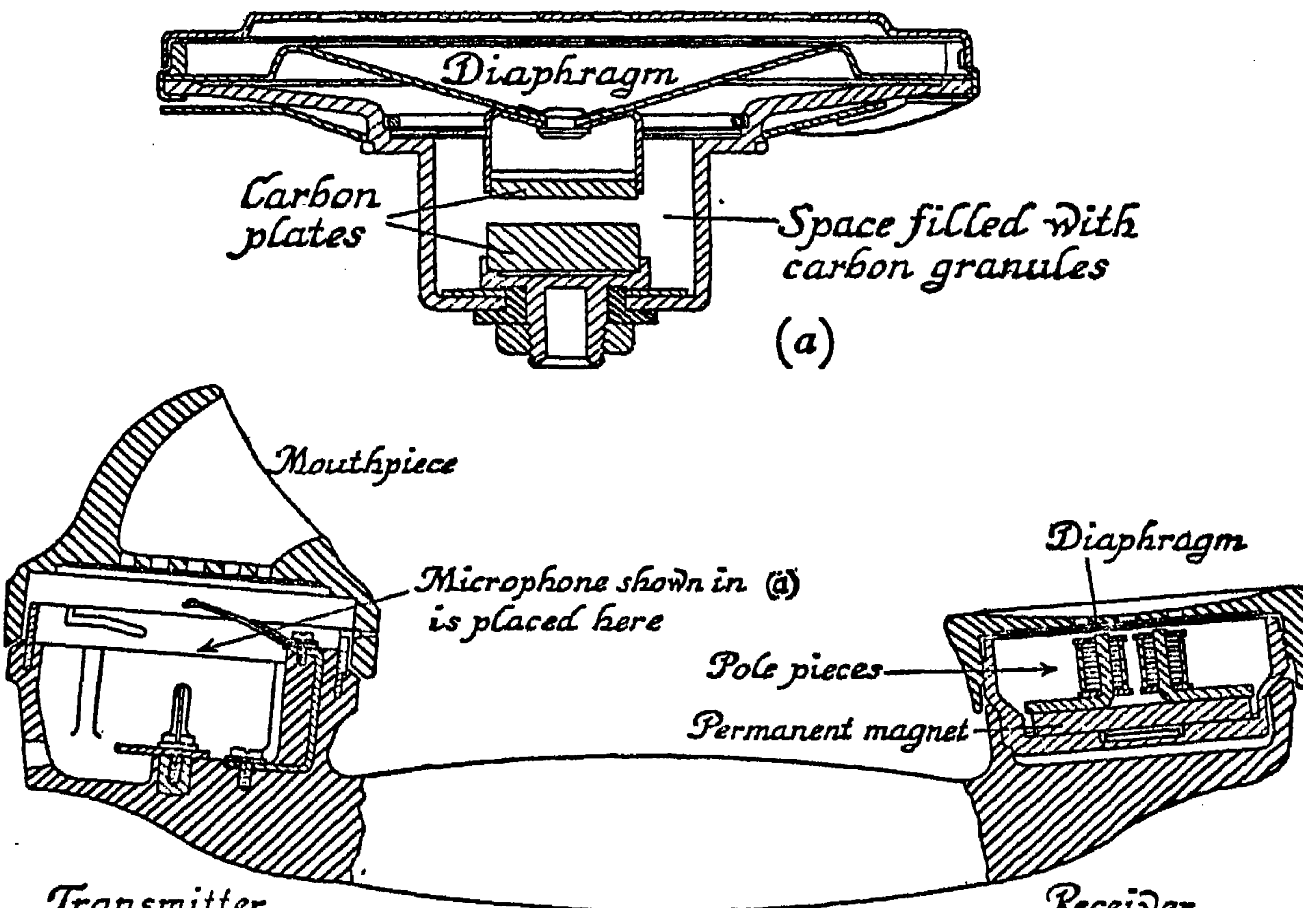


Fig. 109. A standard type of combined telephone transmitter and receiver. (*Post Office Engineering Department.*)

opposite direction decreases it. As we shall see below, the current is generally sent to the receiver through a transformer. If its oscillations had a frequency of 500 and the current were sent round a simple soft-iron electromagnet, it would give 1,000 pulls per second, because a current running either way would create a field. By using a polarizing magnet, as it is called, the true frequency of 500 is repeated. The polarizing magnet also increases the efficiency, because the

variations in the pull on the diaphragm due to weak currents are greater when there is already a pull due to the permanent magnet.

In the original telephone invented by Bell, both transmitter and receiver were like the receiver just described. When one spoke into the transmitter, the vibration of the iron plate altered the magnetization of the pole pieces, by altering the air gap across which the lines of force had to pass. This in turn induced currents in the coil, which were sent to the receiver.

The successful performance of a transmitter and receiver depends upon the faithfulness with which the sounds are reproduced after being converted into electrical signals. We give the telephone a very hard job to do. As has been said above, we can hear notes over a range of frequencies between 15 and 15,000. If the sound which comes out is to be exactly like the sound which goes in, the diaphragm at both ends should respond equally to all these different frequencies, showing no favouritism by sending some notes better than others. Now a diaphragm which is clasped firmly around its edge has a note of its own. A heavy diaphragm stretched slackly has a low characteristic frequency, and a light one stretched tightly has a high frequency. If set in vibration by external forces, a diaphragm responds most strongly to frequencies in the neighbourhood of its own note, exaggerating these and suppressing others. It is this false reproduction which gives the 'tinny' sound on poor telephones or cheap gramophones. Careful design of the diaphragm and of its support does a great deal to increase its range of response, but it is impossible to do justice to the 15–15,000 range in a telephone instrument.

The solution of the difficulty is interesting. The transmitter and receiver are designed to do the best possible justice to all frequencies between 300 and 2,500, because this range covers the vowel and consonant sounds which characterize speech. Now the main frequency of a man's voice ranges around 120, and of a woman's 240[1] (an octave higher), both being below the effective range of the telephone. These notes are deliberately sacrificed in order that the speech-notes may be clear. When we are listening to a friend's voice over the telephone, it is very hard to believe that the telephone is barely transmitting the main tone at all, but this is actually the case. We are so used to making allowances, that we believe we are hearing his or her ordinary speaking voice. Actually the telephone only transmits its overtones, together with the high vowel and consonant notes, and our ears partially reconstruct the rest. To realize this, stand near someone who is telephoning and compare the general tone of the speaker with the tinny scratchy noises coming from the receiver. We recognize what is being said because the all-important vowel frequencies are faithfully rendered.

7. A SIMPLE TELEPHONE CIRCUIT

Fig. 110 shows a diagram of a type of telephone circuit which has now been largely replaced by a more convenient form, but as is so often the case the earlier type is much the easier to understand. Nowadays when we make a call we simply lift the receiver, but with earlier instruments we had to turn a handle to 'ring up' or 'ring off.'

In all forms of instrument the receiver normally

[1] Slightly less than the frequency of middle C on the piano.

hangs on a hook, or rests on a crutch. When we take the receiver off, this hook jumps up and alters certain contacts. If the hook in the figure is down, the telephone is ready to receive a 'ring,' because the bell is connected across the wires marked 'Line.' When the receiver is lifted by someone who is answering the call,

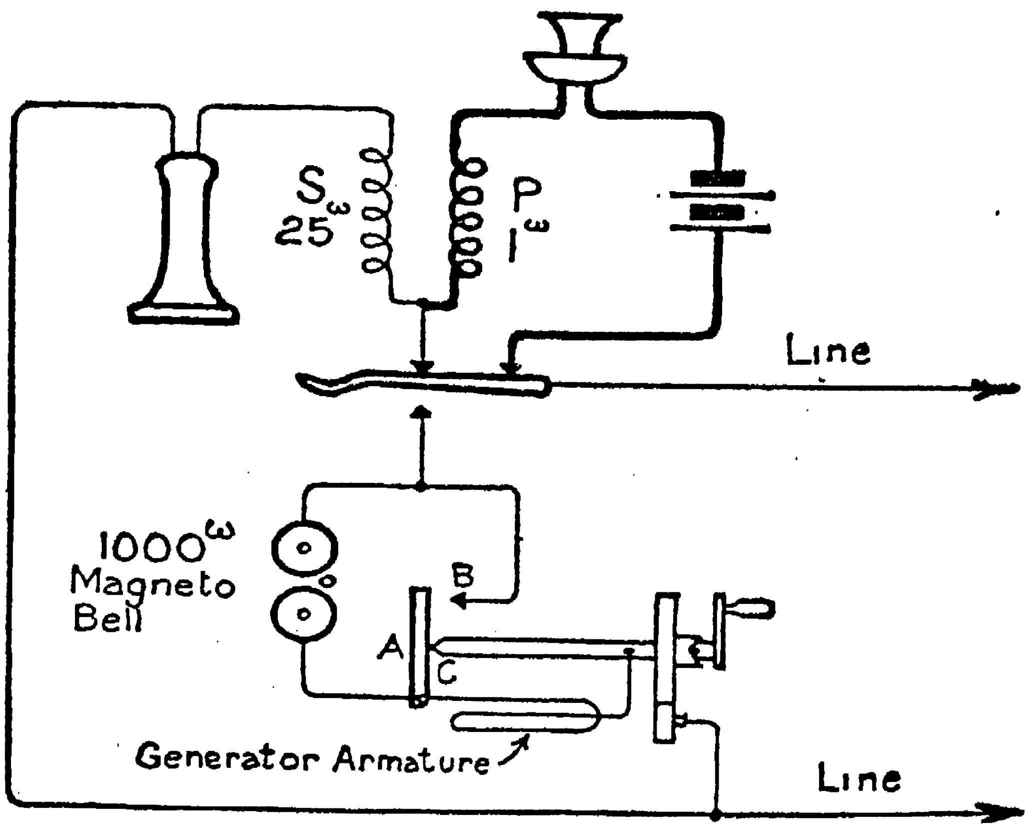


Fig. 110. A magneto telephone circuit.

the hook jumps up. The bell is cut out of the circuit, and the receiver and transmitter are connected to it as in the figure. It is for this reason that we must replace the receiver after a call, for as long as it is off the hook no one can ring us up.

If the subscriber is making a call, he turns the magneto handle, which drives a small dynamo and sends a current along the line to ring the bell at the other end. The handle has got an arrangement by which its axle is displaced to the right for a short distance while it is being turned. You can notice this if you

have one of the old-fashioned instruments. This movement makes A touch B and short-circuits[1] the bell, so that the caller does not ring his own bell and so bring someone else in the house to answer it when he is really ringing up another subscriber.

Then you will notice that the microphone and battery form a little local circuit of their own, linked to the line by the primary P and secondary S of a transformer. The reason for this is that the line has a large resistance, which would quite swamp the small changes in resistance of the microphone if they were part of one circuit. The line resistance cannot be overcome by increasing the voltage, because a carbon microphone makes crackling noises when more than 3 volts are placed across it. We therefore have a low tension circuit of small resistance for the microphone, and transform up before sending current along the line just as in power transmission.

This type of instrument is inconvenient because it has a battery which has to be inspected regularly, and also because people so often forget to 'ring off' when they have finished speaking, so that the operator at the exchange has no warning that they are finished and keeps the lines connected up. Telephones are now worked by a big central battery at each local exchange, which supplies the current to the subscriber's microphone when he lifts his receiver. The connections become much more complicated in this case, and I will not attempt to describe them.

[1] We 'short-circuit' a piece of apparatus when we provide an alternative path for the current of such low resistance that practically all the current goes by this path and not through the apparatus.

8. EXCHANGES

An exchange worked by operators who link up one subscriber's line to another is called a manual exchange. When the connection is made mechanically by 'dialled' signals it is called an automatic exchange. Automatic machinery is now replacing operators to a large extent, but if we see how a manual exchange works it will help us to understand what an automatic exchange has to do.

On the switchboard in front of an operator (Fig. 111, Plate 30) there are rows of sockets connected to the subscribers' lines, and the operator has flexible cords with a plug at each end which can be inserted in these sockets so as to link two lines together. The sockets or 'jacks' are of two kinds. In the first place, the operator has a lower set of about 125 jacks connected to subscribers who are her own especial care. If one of these rings up, a shutter falls above the jack, and she plugs in one end of a connecting cable called a cord. This automatically connects her own earphone to the line, so that she can hear the number wanted. The upper group of jacks is much larger and represents *all* the subscribers on the exchange. This set is repeated at intervals on the switchboard, so that each operator can connect one of her own group of subscribers to anyone else on the exchange by putting the other end of the cord in the right jack. By pressing a switch on the cord, she can send a ringing current to the telephone of the person who is being called.

At another part of the long switchboard there are operators who are attending to calls coming from other areas. They have within their reach a similar

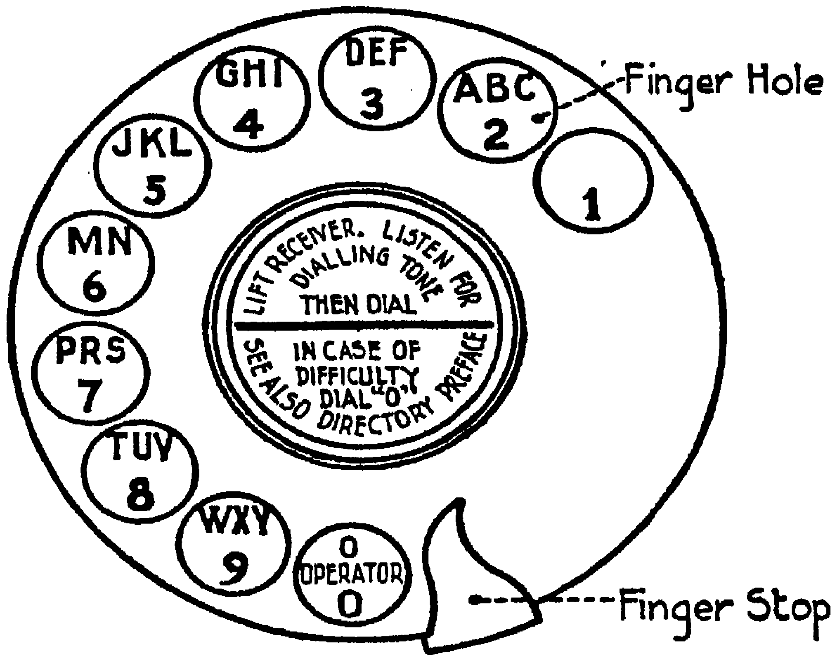


Fig. 112 (*a*)

Fig. 112 (*a*). The dial of a telephone connected to an automatic exchange.

Fig. 112 (*b*). Mechanism of the dial. The governor controls the rate at which the impulse wheel runs back after being displaced, and each tooth on the impulse wheel causes a short interruption of current. (*Post Office Engineering Department.*)

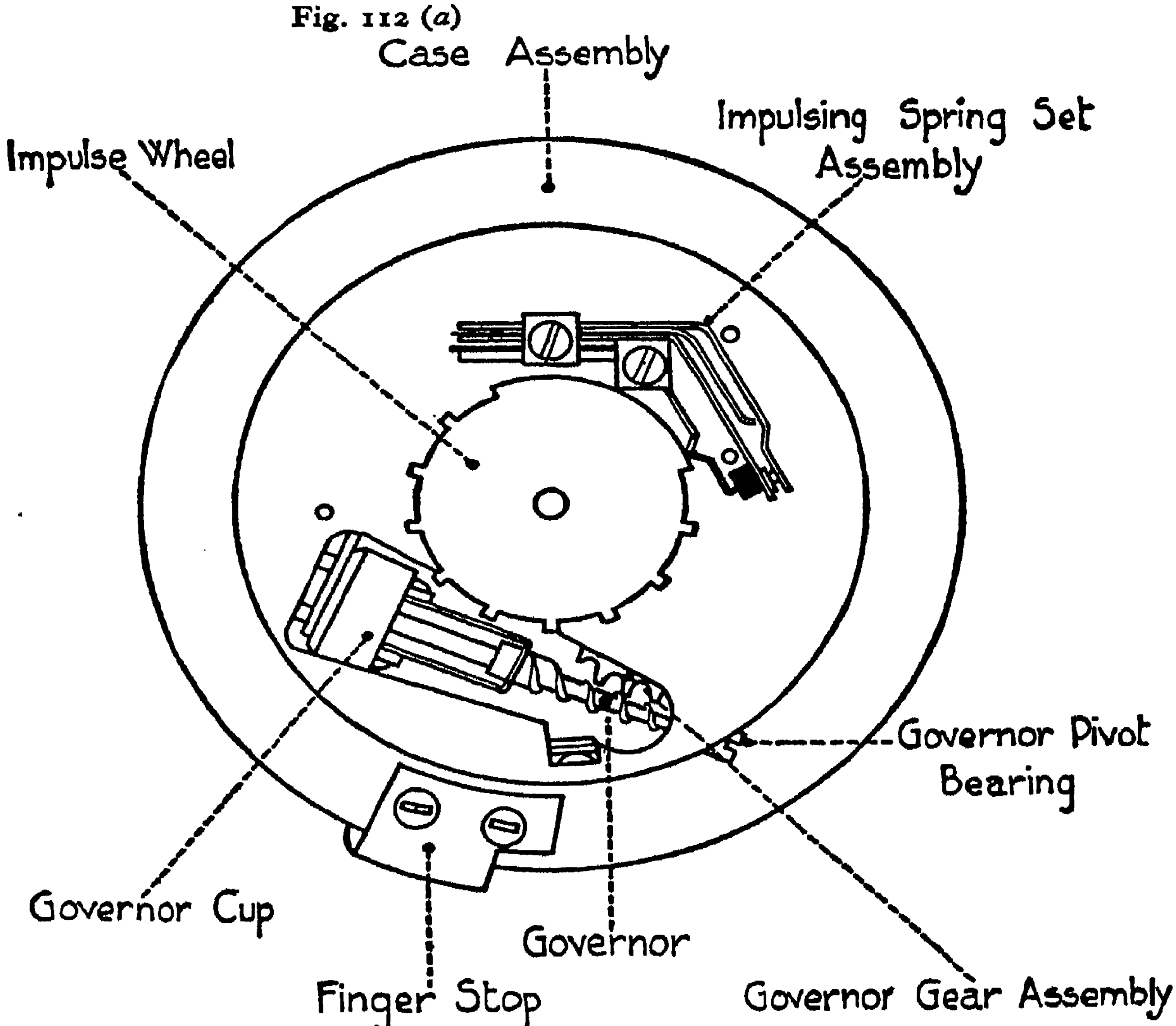


Fig. 112 (*b*)

upper group of jacks connected to all local subscribers, but the lower group represents about 30 lines coming from neighbouring telephone exchanges. When we are putting through a call from one area to another served by manual exchanges, we can hear our local operator repeating the number to the operator of the other exchange. Our telephone line, to sum up, is connected to one socket in front of the operator responsible for attending to our calls, and to many sockets on the upper part of the switchboard, within reach of all operators, so that anyone can call us up. You can imagine what a maze of wires there is behind the switchboard of a large exchange. There are little lamps on the cords which light up when the subscribers have finished their calls and hung up the receivers, so that the operator knows when to clear the line.

An automatic exchange is extremely complicated. I think we will have to be content with seeing how an automatic exchange with a hundred subscribers works, and just getting a hint of how it is done on a large scale.

We send the signals which work the automatic exchange by means of the dial (Fig. 112). When the receiver is lifted a current runs from the battery at the exchange along the lines and through our instrument. If we put a finger in the hole marked 7 on the dial, pull it round to the stop, and let go, this current is broken seven times as the dial runs back. It is these short breaks in the current which work all the automatic machinery.

Fig. 113 shows the machine called a 'Selector' which is worked by the dial. You will see at the bottom ten

rows of ten contacts, a hundred in all, to which the hundred subscribers' lines are connected. When we are ringing up, our line is connected to the arm at the bottom (really the arm is double and each contact is double because we have to connect our two lines to someone else's two lines). When we dial 7, the seven *interruptions* of current on the line make (by means of a relay) seven *pulses* of current run through the magnet marked VM. This magnet attracts its armature and makes a little catch or 'pawl' marked VP lift up the shaft by one tooth for every pulse of current, and the arm at the bottom rises to the level of the seventh row of contacts. When we dial the next number, say 3, the pulses of current now work the other magnet marked RM. The pawl marked RP turns round the shaft one tooth for every pulse of contact, and therefore connects the arm to the third contact of the seventh row, which is of course

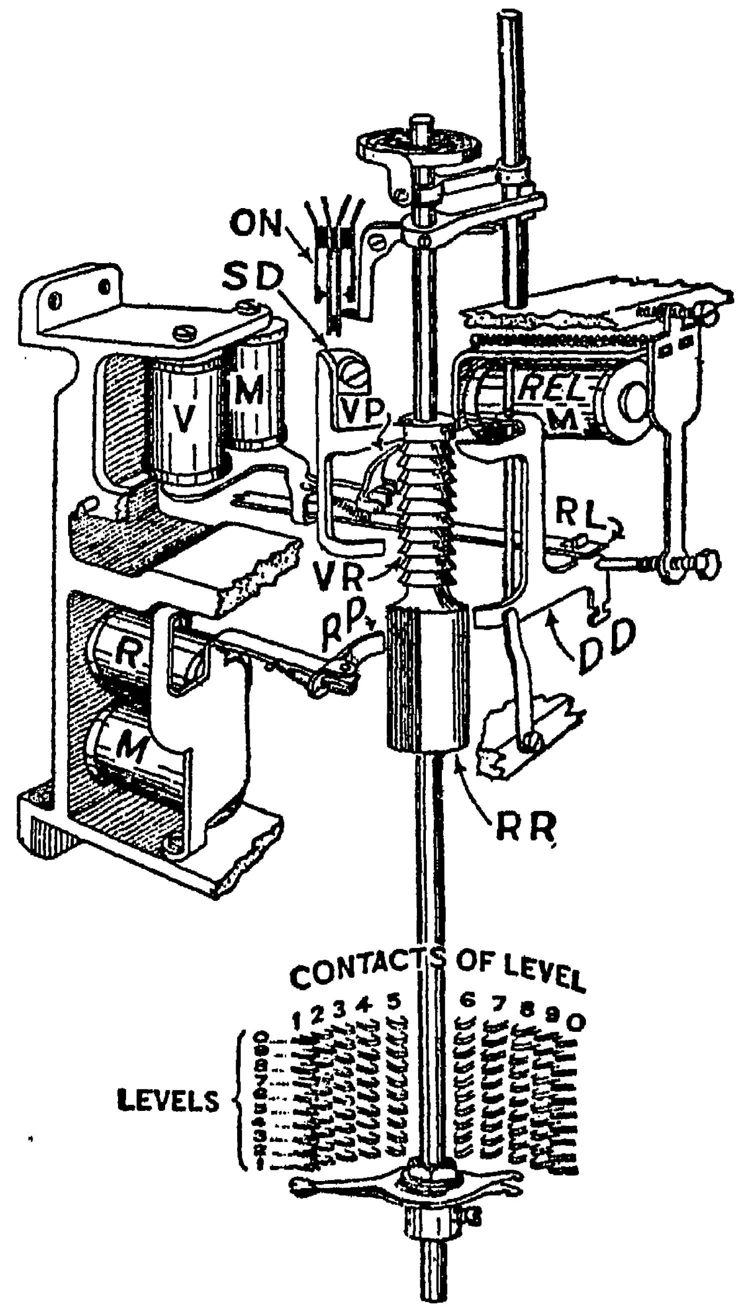


Fig. 113. A 'Selector' in an automatic telephone exchange. (*Post Office Engineering Department.*)

No. 73, the subscriber we want. When we have finished talking and the receivers at each end are hung up, the release magnet marked Rel M releases the catches, and the spiral spring at the top pushes

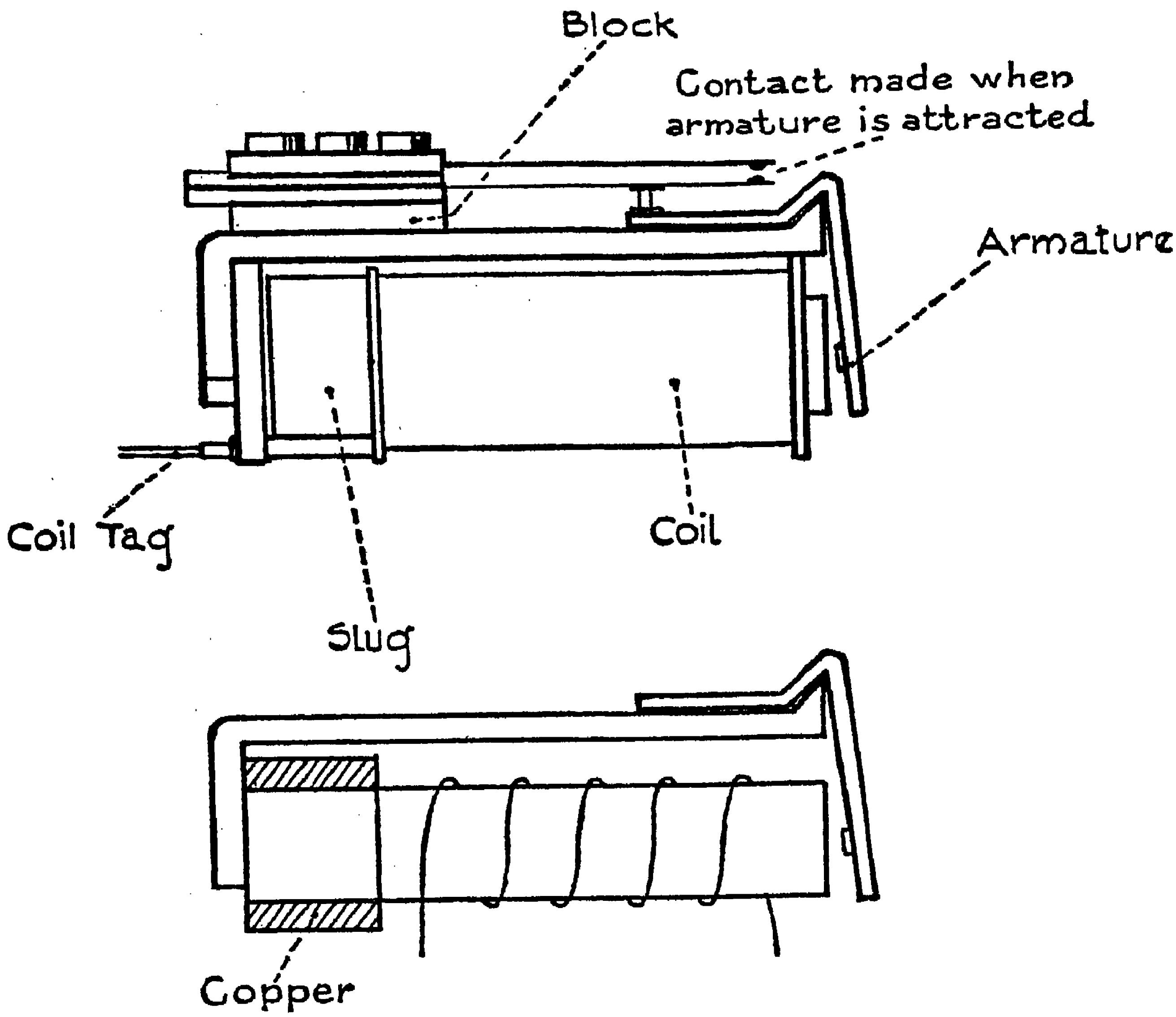


Fig. 114. A 'slow-to-release' relay, with its copper 'slug.'

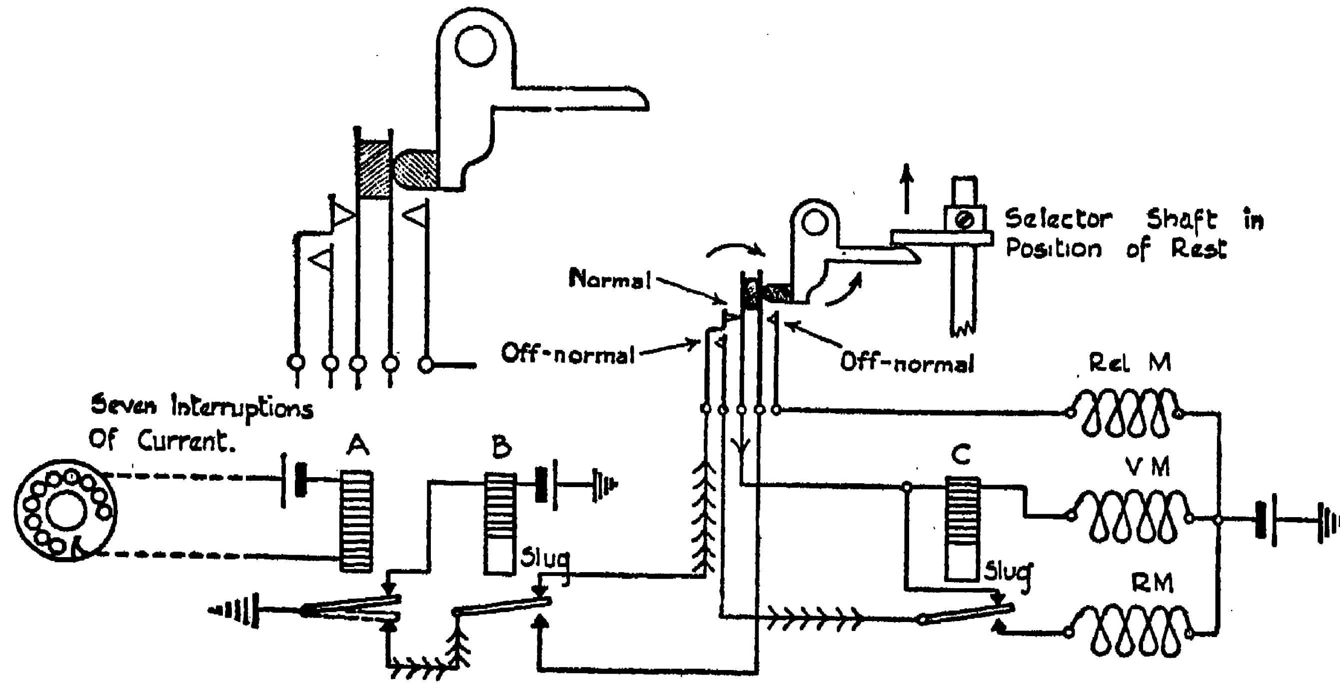
the spindle round so that it can fall back into the normal position and be ready for another call.

The tricky part to understand is this – how is it arranged that the first seven impulses work VM and the next three work RM? If this essential point is grasped, I think the reader will be content to take the rest of the devices on trust, for it will be clear that the

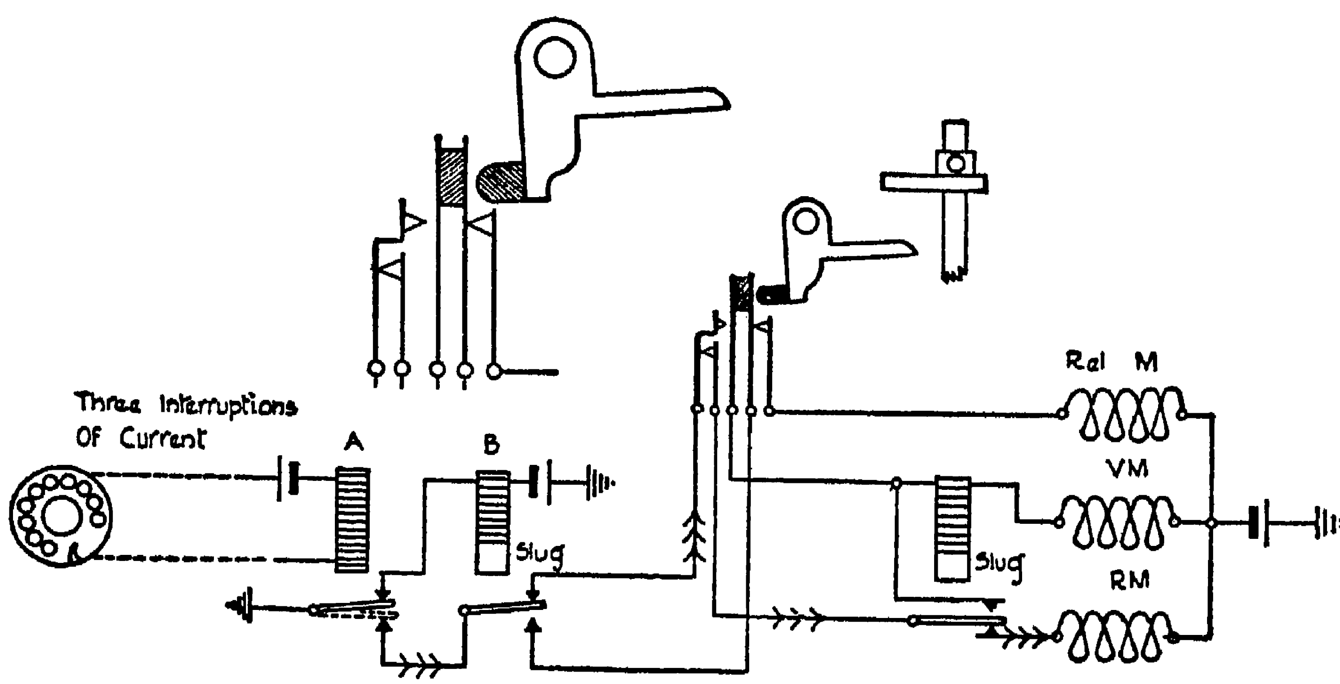
provision of apparatus for calling one of a very large number of subscribers is only a matter of using the same device several times over.

The signals are made to work the right magnets by the 'slow-to-release' relay shown in Fig. 114. When a current flows the armature is attracted and the contacts at the top are made to touch, and when the current ceases they are parted again. This particular relay, however, has got a solid collar of copper called a 'slug' around its iron core. When the current is switched off, a current is induced in the slug in such a direction as to retard the dying away of the magnetic field. The heavy copper collar has so low a resistance that this induced current only dies away slowly, and the magnet does not release its armature till half a second or so after the current in the coil has stopped. This cunning device makes it possible to send short interruptions of current through the relay without its taking any notice of them; it is only when the current stops for more than half a second that its armature is released.

Fig. 115 shows how a slow-to-release relay is used to steer the first group of signals through VM and the next set through RM. There are three relays in the circuit, marked A, B, C. A is an ordinary relay which makes and breaks immediately; B and C have slugs. In addition there are certain contacts which are worked by the shaft of the selector. When it is in its normal position before a call is made, the contacts marked 'normal' touch. Directly it is raised up by the magnet VM (see Fig. 113) its weight is taken off a lever, and this breaks the contacts marked 'normal' and makes the two contacts marked 'off-normal.'



(a) The First Seven Impulses Go Through VM



(b) The next Three Impulses go Through RM.

DIALLING THE NUMBER 73

Fig. 115. A plan illustrating how the signals from the dial work the selector. Note especially the alteration of the 'off-normal' contacts when the selector shaft rises (the contacts are shown on a larger scale in each diagram).

The rest of the connections can be seen on the diagram.

Now let us raise the receiver, dial a number, have a conversation, and put the receiver back.

(1) When we raise the receiver, a battery drives a current along the lines, through our telephone, and through relay A. A's armature goes up and a current goes through B. B's armature goes up and all is ready for our dialling.

(2) We put our finger in hole 7, move it round to the stop, and let go. As the dial runs back, it cuts off the current seven times. A's armature drops seven times, and this sends seven impulses of current along the route shown by the seven little arrow marks. Of course B has its current cut off seven times, but as it has a slug it takes no notice.

At the start the shaft of the selector is in the normal position. The first current impulse therefore runs through the 'normal' contact, through C, and through the magnet VM. The shaft goes up one notch, and at the same instant C pulls its armature up. Since the shaft has gone up, the 'normal' contact is broken and 'off-normal' is made. The next six current impulses go by the other route through 'off-normal,' but, since the C armature is raised, they join on to the first one and all seven go through VM. I have drawn the first impulse as an arrow on one wire, and the next six on the other; the figure is much easier to follow than a written account.

(3) We now put our finger in hole 3 and pull it round to the stop. This takes a little time to do, and the pause is too much for relay C. It has held its armature up with the aid of the slug while the first seven impulses run through it, but now it has to let go.

The next three impulses run through RM, and link up our line to No. 73.

(4) We have a talk.

(5) We put the receiver back. This cuts off the current through the lines, and A lets its armature drop. B then lets its armature drop, and the current runs through the other 'off-normal' contact and the release magnet (Rel M). This trips the selector shaft, which rotates and drops to the normal position, and everything is as it was when we started.

Perhaps you will now see why the contacts I have marked 'normal' and 'off-normal' are needed, though at first sight they seem an unnecessary complication. If 'off-normal' were connected the whole time, all the first impulses would take that path and run through RM, for C would never lift its armature. The 'normal' contact at the start makes the very first impulse lift C, and all the others of the first group can then follow it through VM.

In an exchange with a hundred subscribers, such as we are considering, it would be too expensive to give each subscriber a selector apparatus all to himself. A calculation is made as to how many subscribers will be likely to be making calls at once at a busy time, and a corresponding number of selectors is provided. The number varies greatly, being much larger for office telephones than for private subscribers, but one selector for every ten lines is an average number. The only apparatus which belongs exclusively to each subscriber's line is a device called a 'uniselector.' When we lift off the receiver, the uniselector finds a disengaged selecting mechanism for us. It is like a porter trying to find us an empty seat in a train. It

has an arm called a 'wiper' which runs round touching contacts leading to the selectors. If a selector is busy it moves on, but directly it finds a disengaged one it stops, connects us to the selector, and everyone else is prevented from using it till we have finished with it.

When dialling a four-figure number, say 9173, a process similar to that which has just been described takes place several times. When we lift the receiver the wiper arm of our own private uniselector runs round till it finds a free 'thousand selector' for us, and connects our line to it. When we dial the number 9, the nine current interruptions raise a wiper arm in this selector to the ninth row of contacts, and the arm then travels round till it finds a connection to a free selector in the next rank, this being a rank of selectors which deal with all numbers beginning with 9000. When we dial 1, the wiper arm of the second selector rises to the first level, and moves round till it finds a free selector in the small group dealing with the numbers beginning 91. Each of these final selectors has the lines from 9100 to 9199 connected to its hundred contacts. The final two numbers 7, 3 thus put us through to subscriber 9173 as already explained.

Of course, this is by no means all, for the machines have to find the right exchange for us, give a dialling tone, a ringing tone, a 'line-busy' tone, and count the number of calls we make so that our bills can be made out. Finally there is a machine called a 'rout-iner' which automatically tests the selector machines one after the other. If all the parts of a selector are in good working order it passes on to the next, but if

anything is wrong it rings a bell and lights a lamp which tells which part is wrong! There is something almost uncanny about an automatic exchange, with all the machines chattering as they make their intricate cross-connections; it is as if one were inside the brain of a living creature, watching it work.

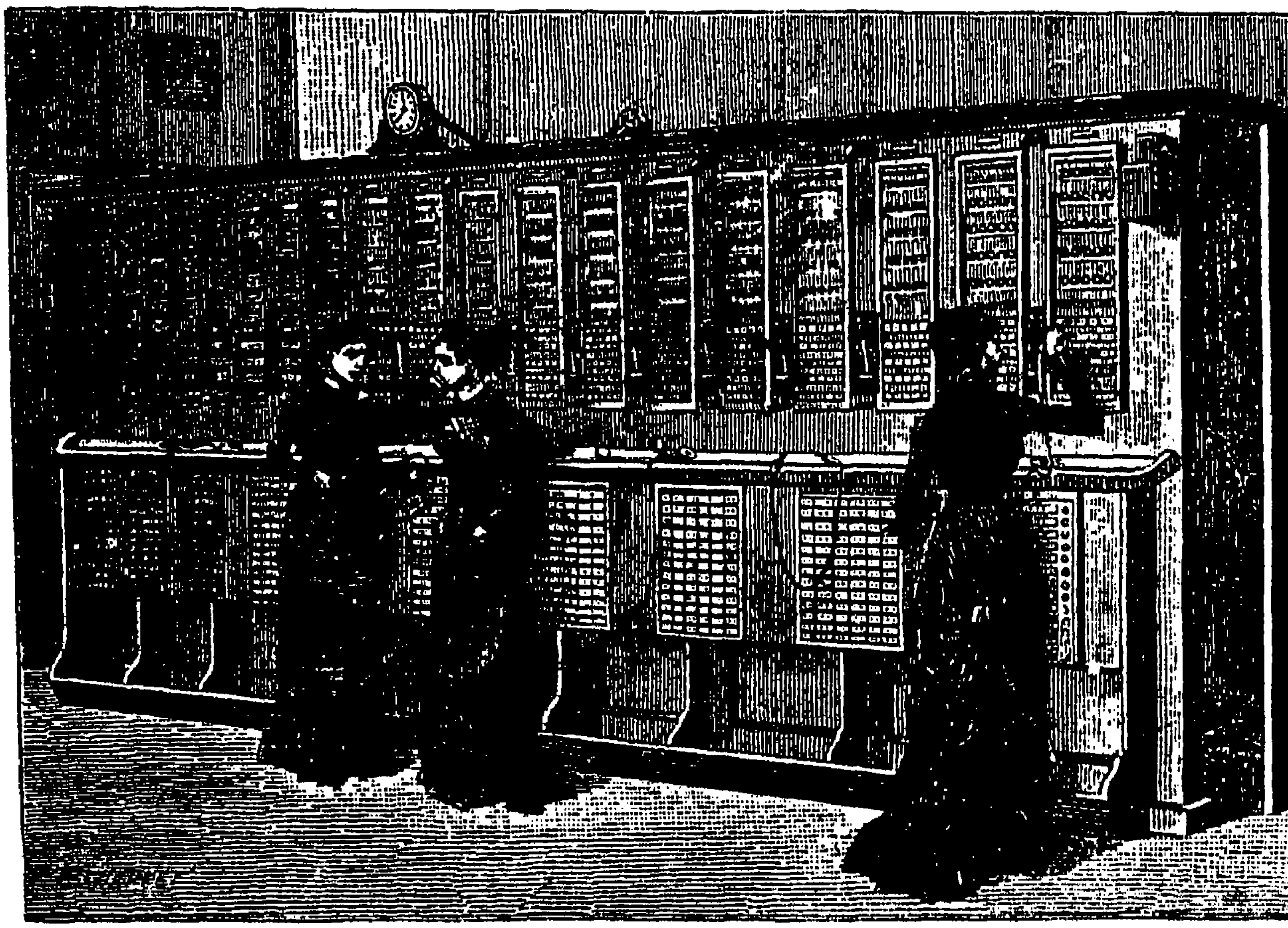


Fig. 116. The Central Exchange in Paris fifty years ago. (*Guillemin's Electricity and Magnetism.*)

The contrast between the modern telephone exchange and that shown in Fig. 116 shows how rapidly the use of telephones has grown. I have taken it from a book by the late Professor Silvanus Thompson; it is the Central Exchange in Paris just over fifty years ago!

9. OVERHEARING

Sometimes when we are using the telephone we can hear other people carrying on a conversation. This does not mean that our lines have by some mistake been connected to theirs. It is due to both parties using circuits which run parallel to each other for a considerable distance. The prevention of overhearing is a science in itself, and the means which are adopted

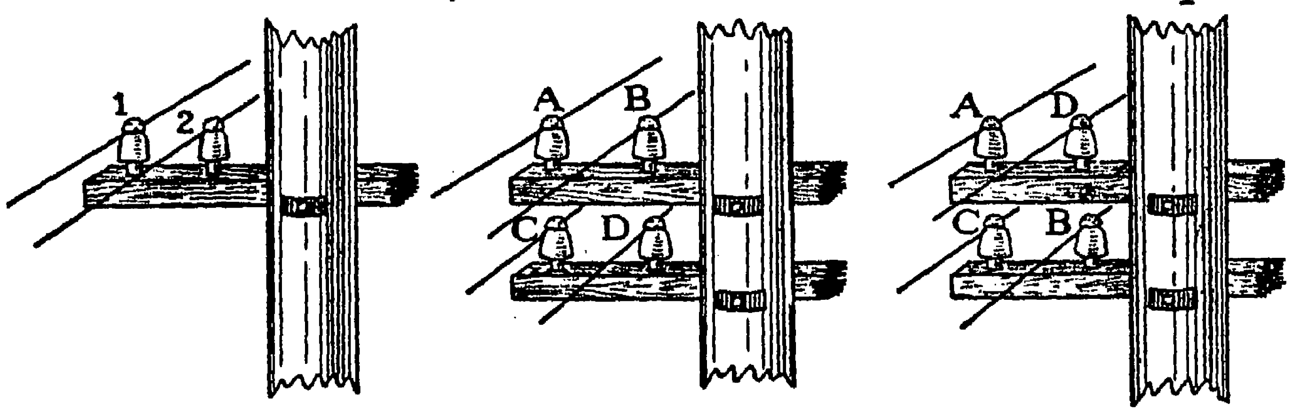


Fig. 117. The elimination of overhearing on parallel telephone circuits.

illustrate some of the principles we have been discussing so well that it is worth while describing them.

To take the most simple case first, let us suppose that each circuit consists of a single wire and an earth return, and that the two wires run side by side along the same poles. We may think of the varying current in one wire which is conveying the speech as a simple alternating current along the wire marked 1 in Fig. 117*a*. This current sets up a similar current in wire 2 in two ways. In the first place, wire 1 is charged + and − alternately by the current. Every time it is charged positively, a negative charge is induced in wire 2, and a positive charge repelled away from it to earth. The opposite happens when it is charged negatively. The result is just as if some of the alternating

current in wire 1 passed into wire 2; the two wires side by side in fact form the plates of a condenser, and an alternating current can pass through a condenser in a way which is well illustrated by some of the examples in the next chapter. In the second place, the alternating current in wire 1 sets up an alternating magnetic field in its neighbourhood which induces currents in wire 2. We thus have effects due to both electrostatic and electromagnetic induction, the first being actually the more important.

There is no possible way of avoiding this effect with single wires running side by side, and it is for this reason that earth returns are never used on telephone systems with a number of lines. As you will notice in places where telephone wires are run to houses from poles, there are always two wires to each house making a complete metallic circuit. Fig. 117*b* and *c* illustrate a way of avoiding interference between a pair of wires AB and a pair of wires CD. It is clear that Fig. 117*b* is a bad way of arranging the wires. If A is + and B −, C will be − and D +, giving electrostatic interference. Similarly if a current runs along A and back by B, a magnetic field is set up whose lines of force pass through CD, giving electromagnetic interference. On the other hand, if we arrange AB and CD as in Fig. 117*c*, all cross effects cancel out. The magnetic lines of force due to AB do not cut the circuit CD, and charges on A or B affect C and D equally, so giving no current.

This provides for non-interference between two pairs of lines; we must now see how to avoid it when there are many pairs on the same poles. Formerly interference was avoided by changing the positions of the

wires from pole to pole. You may have noticed this device when watching wires from the window of a railway train. As they swoop up and down from one insulator to the next, the whole pattern changes, because some wires pass from a cross-arm on one pole to one higher or lower on the next pole, or move by one insulator in or out. Each group of four wires is every now and then given a complete twist, so that if it has

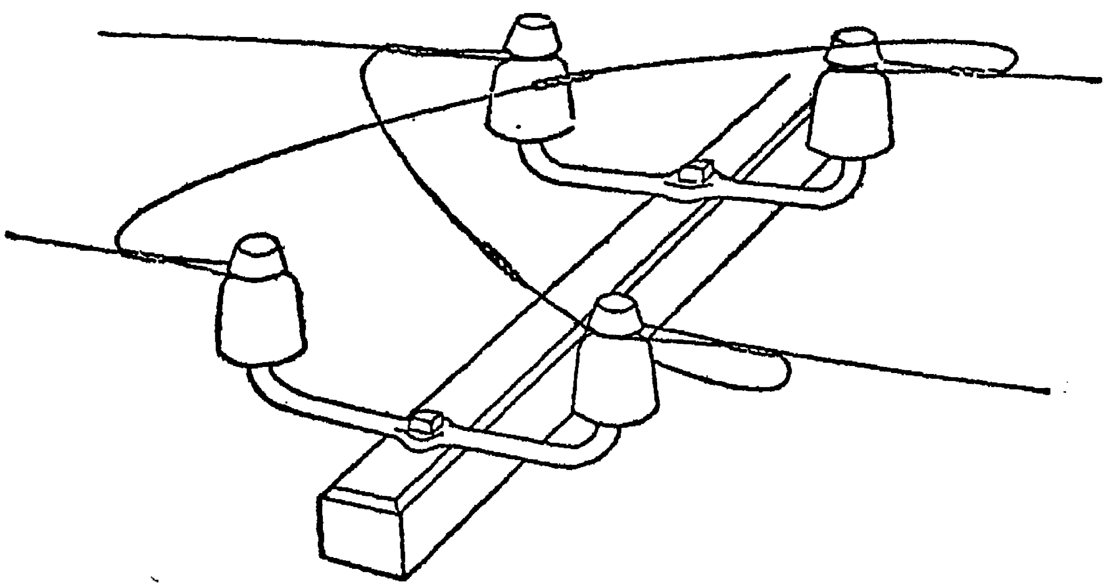


Fig. 118. Method of transposing telephone wires to prevent overhearing.

been affecting a neighbouring circuit in a certain way for the last mile, its effect will be just the opposite for the next mile. By giving the various groups twists at judiciously chosen intervals, all cross effects can be cancelled.

The same effect is now realized in a less elegant but more convenient way by transposing the wires of each circuit at intervals as shown in Fig. 118. If in Fig. 117*b* the wires of circuit AB are transposed at every quarter-mile so that A takes B's place and vice versa, the net effect on CD can at most be that due to an odd quarter mile at one end, which is negligible.

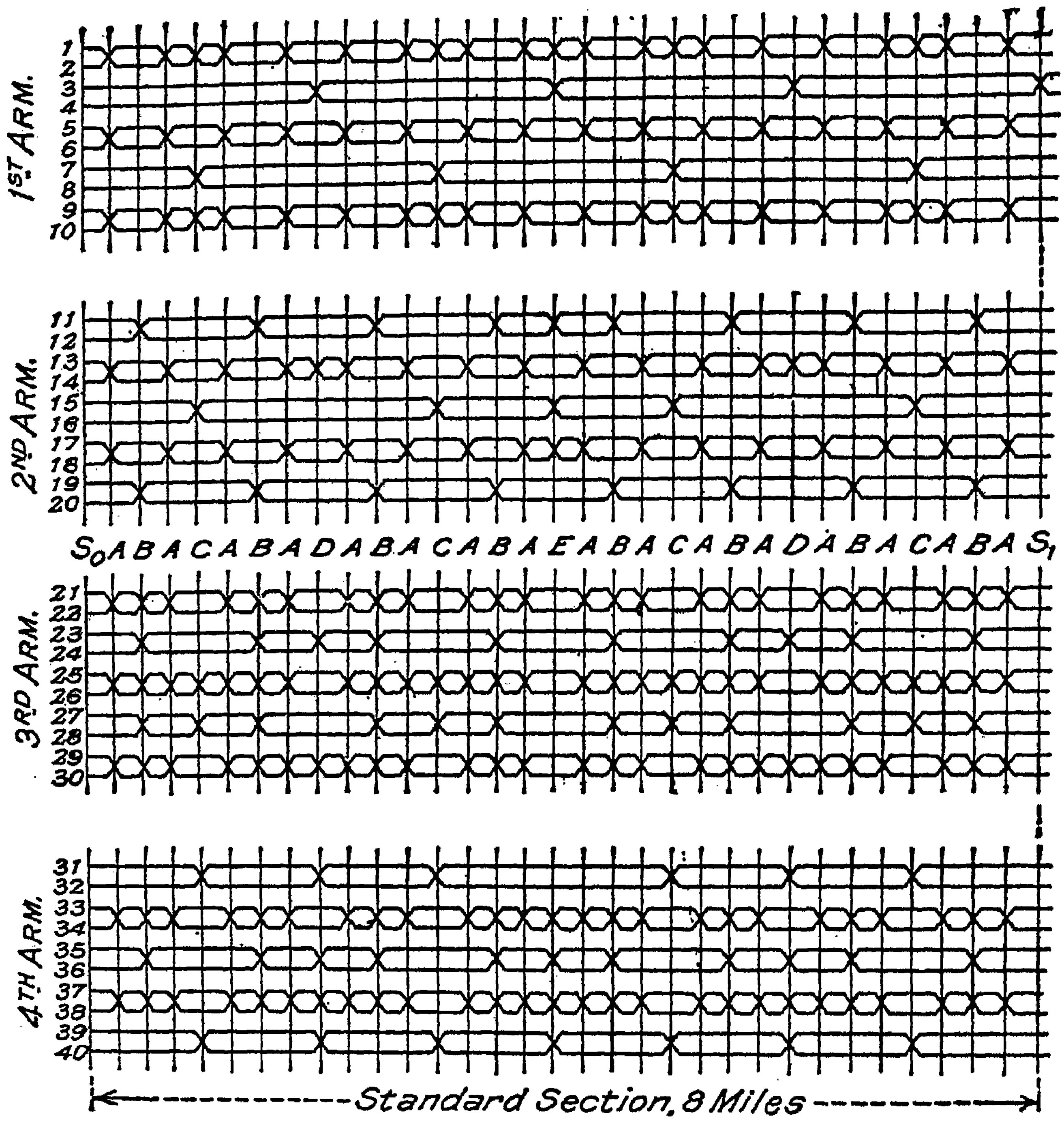


Fig. 119. System of crossing telephone wires to prevent overhearing, designed for twenty overhead circuits. (*Post Office Engineering Department.*)

When we add a third circuit EF, we must not transpose it at the same points as AB, or AB and EF will interfere, but if, for instance, we transpose it each half-mile, it will not interfere with either AB or CD. Just for interest, I have given the scheme for twenty

circuits on poles in Fig. 119. Each interval between two upright lines represents a quarter of a mile, and the pattern is repeated every eight miles.

Underground cables are now replacing the big overhead trunk lines, because they are more free from breakdowns and require less maintenance. The prevention of overhearing is a delicate matter because the wires

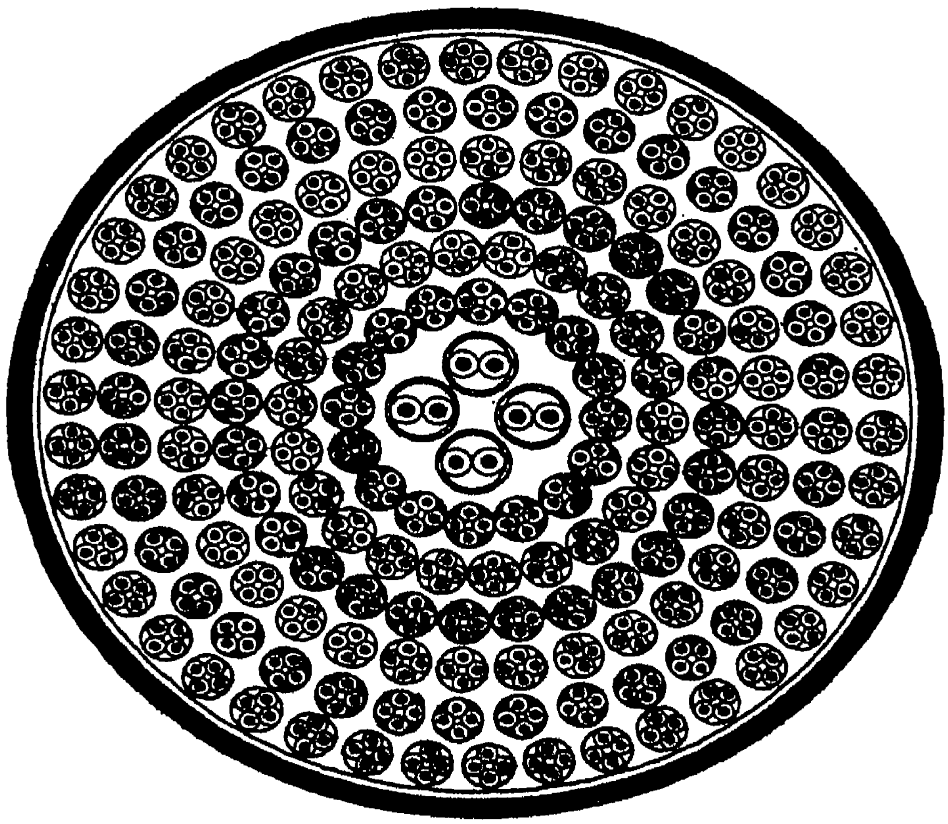


Fig. 120*a*. Section of telephone cable containing 350 pairs of lines. (*Post Office Engineering Department.*)

in the cable are so close, and there may be more than a thousand pairs of them. Fig. 120*a* shows a diagram of a cable. You will notice the wires in fours, each being a pair of circuits like AB and CD in Fig. 117*c*. These groups must be twisted so as not to interfere with each other, and must all be twisted at different rates as they run along, because if any two had the same twist their cross effects would build up. The four large circuits in the centre are for transmitting

broadcasting programmes. A piece of actual cable, dissected so as to display the circuits, is shown in Fig. 120*b* (Plate 29).

Finally, when a long trunk cable is being joined up, electrical measurements are made on all the pairs in each section to find their mutual effects, and a programme is drawn up for joining the individual pairs together when the sections meet so as to reduce interference to a minimum. A long trunk cable has valve amplifiers at intervals, like those in a wireless apparatus, which boost up the telephonic currents which would otherwise become too weak. It has loading coils, which lessen distortion of the signals, like the loading on a submarine cable. All these devices must be balanced so that 'phantom' circuits can be used as already described. It would seem such a simple matter to join a number of telephone wires together, and yet we see when we go into detail that a trunk cable is as much a work of craftsmanship, and has required as much ingenuity and design, as a bridge or a building

CHAPTER VI

OSCILLATING ELECTRICAL CIRCUITS

1. OSCILLATIONS

We can construct an electrical circuit which behaves in the following way. If a current is set running in, or an electrical charge is given to, some part of the circuit, and it is then left to itself, electrical *oscillations* take place. A current surges backwards and forwards in the circuit like water surging backwards and forwards in a trough and piling up at each end alternately. If no further energy is supplied, the electrical oscillations die away, owing to the resistance of the circuit and other damping factors. On the other hand, various devices can be used to supply further energy and maintain the circuit in continuous oscillation.

Oscillatory electrical currents play an essential part in wireless telegraphy and telephony. It would be beyond the scope of this book to go into the technical details of the apparatus used for wireless. One must know the properties of oscillating circuits, however, before one can understand the principles of wireless, and I will try in this last chapter to make their nature clear.

We may start by considering oscillations of a mechanical type, such as those of a weight at the end of a spring (Fig. 121*a*) or these of a pendulum (Fig. 121*b*). If we pull the weight down and let it go, it

bounces up and down at the end of the spring. Let us consider in detail what is happening.

When at rest, the weight extends the spring to the

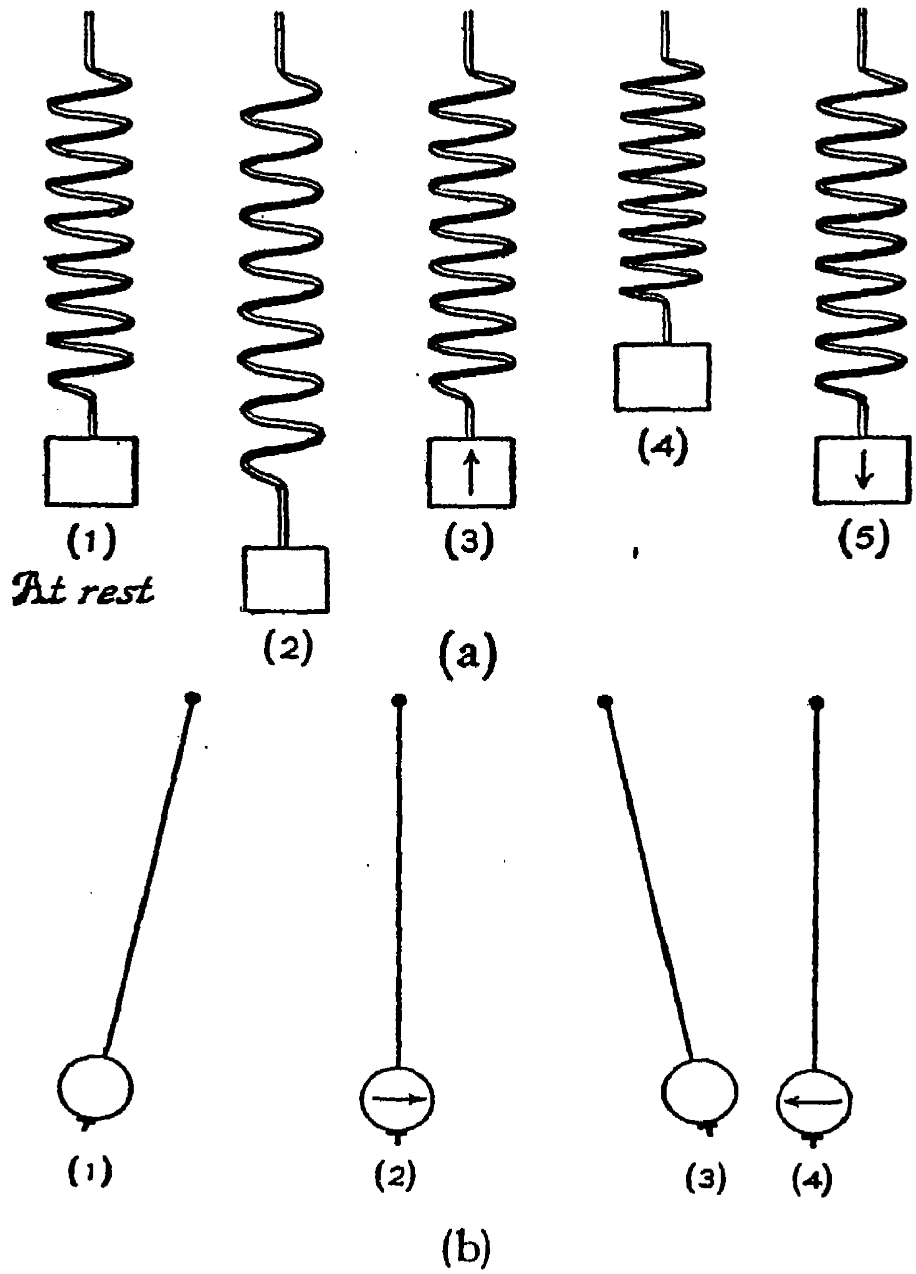


Fig. 121. Oscillations of (*a*) a weight on a spring, (*b*) a pendulum.

extent shown in (1). If it is pulled down further, as in (2), the tension of the spring is increased, so that the weight flies up when released. In (3) the weight has got back to the normal position. No force is now acting on it, because the pull of the spring just balances the pull of gravity on the weight. It does not stop in this

position, however, because it got up speed while the spring was pulling it up. It runs through the normal position to that shown by (4), when it comes momentarily to rest again. The pull of the spring is now less than the pull of gravity and the weight falls, running through position (5) till the spring is again extended, when the movements repeat themselves. If there were no losses due to friction the weight would go on oscillating for ever. Actually, its oscillations gradually die away.

The same happens when the bob of a pendulum is pulled to one side and released. It is drawn by gravity back to the normal position, but having got up speed it moves past it to the other end of its swing, and then retraces its path.

It is an essential feature of such oscillations that the energy fluctuates between two forms. Work has to be done to pull the bob of the pendulum to one side. When the bob is displaced, this energy is stored up as 'potential energy.' When it is let go and swings down to the normal position the potential energy has disappeared, being changed into the 'kinetic energy' of the moving bob. The kinetic energy is used up in driving the bob to the far end of its swing, becoming potential energy again. If you think of any form of oscillation (balance wheel, piano string, tuning fork), you will realize that there is always this alternation of energy between two forms.

An oscillating system such as we have been considering always takes the same time to make a to and fro movement, whether it is making a small swing or a large one. We might think that it would take longer for a pendulum to swing over a large arc than over a

small one, because it has further to go, but this is not the case. When it is swinging over the large arc, it moves proportionally faster. The discovery that a pendulum beats at the same rate whatever the extent of its swing led to the construction of the first clocks. If this law did not hold, our clocks would be very poor timekeepers, because their rate would depend on how much they were wound up. Musical instruments provide a very sensitive test. The oscillating systems in this case are stretched strings or columns of air in tubes. A note on the piano is of the same pitch whether struck loudly or softly, so that clearly the rate at which the string vibrates is independent of extent of vibration.

The number of oscillations made in a second is called the 'frequency,' and the time required for a complete oscillation is called a 'period.' The whole series of movements during a complete period is often termed a 'cycle' and instead of frequency we may speak of so many cycles a second. The extent of the greatest displacement from the normal position is called the 'amplitude.' An oscillating system has the same frequency, whatever its amplitude, if it obeys the following simple law. The restoring force which tends to pull it back to normal when it is displaced must be proportional to the displacement. All common oscillating systems obey this law. For instance, if a spring is extended by two inches, it will pull twice as hard as if extended one inch. When the bob of the pendulum is pulled six inches to one side, the force on it is twice as great as when pulled three inches to one side. As a consequence it moves twice as fast through its position of rest, and for this reason keeps the same time as when it has the smaller amplitude.

What determines the frequency of the oscillations? I must adhere to my rule of avoiding mathematical equations, for our object is merely to acquire common-sense and an instinctive feeling for the way things work. To take the weight on the spring as an example, you will realize that the rate at which it oscillates depends on two factors. The first is the stiffness of the spring. When it is made of tight coils of thick wire, the weight dances up and down rapidly, whereas if it is made of open coils of thin wire its period is much longer. The second factor is the massiveness of the weight. A weight of small mass has a short period, a more massive weight a longer one. To put this more exactly, we make the vibrations more rapid when we increase the restoring force for a given displacement, and we make them slower when we increase the mass to be moved. It is perhaps worth considering how these rules work in the case of the pendulum. Suppose we make the bob twice as heavy, keeping the length of the pendulum the same; will it beat faster or slower? We have doubled the mass to be moved, but at the same time we have doubled the force pulling the bob back when it is displaced by a given amount. The net result is that the pendulum beats at exactly the same rate as before. In fact we might think of two identical pendulums swinging side by side. They will beat at the same rate, and we may therefore join the two bobs together and call it a single pendulum with a bob twice as heavy. All grandfather clocks which beat seconds have pendulums of the same length. If we shorten the pendulum, on the other hand, the force pulling it back when displaced the same distance side-ways is increased, and the shorter pendulum beats faster.

Oscillations can be kept up if the moving body is given a slight push during each period, timed so as to drive it in the direction in which it is already moving. A familiar instance of this is a swing. A child who is swinging a companion gives a push to the swing each time it moves away, so as to hurry it up slightly. The period of the swing is not influenced by these pushes; one cannot make it go backwards and forwards more times a minute by pushing harder, one can only increase the amplitude.[1] We must adapt our impulses to what is called the 'natural period' of the swing.

It is characteristic of most systems designed to be maintained in oscillation that the machinery for keeping up the oscillation is considerably more complicated than the part which oscillates. Nothing could be simpler than the pendulum of a clock, or the balance wheel and hairspring of a watch, but the cogs and levers driven by springs or weights which keep them moving are quite tricky bits of mechanism. They are designed so as to give the necessary impulses which always encourage the pendulum or wheel to move a little faster in the direction it is already going. We shall find the same thing in the case of electrical circuits. A large power valve and circuit for maintaining electrical oscillations, such as is installed at a radio transmitting station, is a very impressive piece of machinery. Yet the part of it in which the electrical oscillations take place is extremely simple, the complex devices serving the purpose of keeping the oscillations going.

[1] This is not rigidly accurate; the period is slightly altered by the impulses to an extent depending on the instants when they are given.

2. ELECTRICAL OSCILLATIONS

Fig. 122 shows the way in which electrical oscillations take place. There are two essential features of the circuit, capacity and inductance.

'Capacity' has already been explained (see page 31). The idea of 'inductance' is a difficult one, and I will try to make it clear in this section. If a length of wire is made into a coil, and especially if a piece of iron is placed inside the coil, so that a current running in the wire produces a strong magnetic field over a large

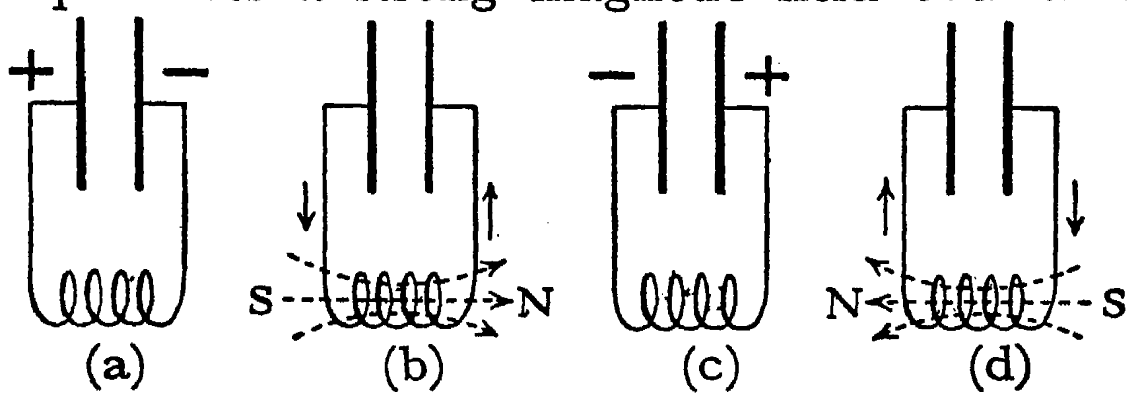


Fig. 122. An oscillatory electrical circuit.

space, the circuit has a *large inductance*. On the other hand, if the same length of wire is doubled backwards and forwards on itself, a current in it will only produce a feeble magnetic field over a small space because the effects of the current in going and returning nearly cancel out; the circuit then has a *small inductance*.

The two sides of a condenser in the figure are connected by a coil such that when a current runs in it a magnetic field is created. Actually any conductor whatever satisfies these conditions, since it will serve as a condenser and will be surrounded by a magnetic field when a current passes in it. For simplicity, however, we will represent the circuit by a conventional condenser and coil of wire as in the figure. Let us now

suppose that we give the plates of the condenser opposite charges, as in (*a*). The condenser discharges through the coil of wire. In (*b*) it is completely discharged. In discharging, however, it has created a magnetic field which I have indicated by the dotted lines of force. The current cannot stop abruptly at this point; as it dies away, the magnetic field inside the coil diminishes and this induces an electromotive force tending to keep the current going. The current runs on till it has charged up the condenser in the opposite sense as in (*c*). The condenser then discharges, creating a magnetic field in the opposite direction, which in turn causes the condenser to charge up as (*d*) at the start. The cycle of events repeats itself and the circuit oscillates.

You see how closely these events correspond to the bouncing of a weight on the end of a spring or the swinging of a pendulum. The charging of the condenser is like compressing and elongating the spring or pulling the bob to one side, representing the storing of energy corresponding to the potential energy in the mechanical vibration. As the condenser discharges, this energy is converted into the form of energy of the magnetic field, which we may compare to the kinetic energy of a mass in motion. The energy of the magnetic field is used up in charging the condenser again, and so on backwards and forwards.

There is the same alternation of energy between two forms as in the mechanical case. The energy of the stored condenser is made obvious by the spark which we can get from it on discharge. As we charge it up we have to do work against the potential difference between the two plates, due to the charge we are putting

on it. It behaves just like a spring, in fact, because the more charge we have already given it, the harder it becomes to put additional charge on it owing to the rising potential, just as the resistance of a spring increases as we pull it out or compress it. The energy of the magnetic field is perhaps not quite so clear, and it

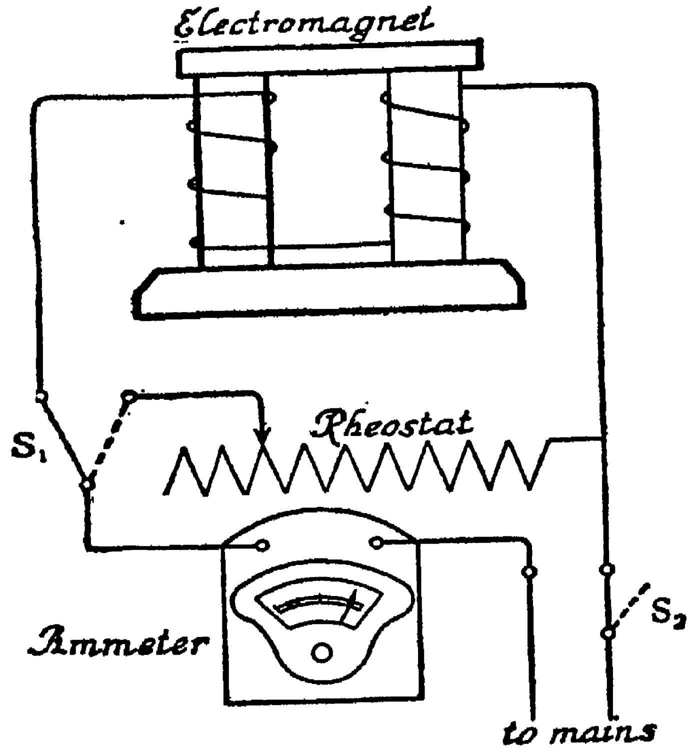


Fig. 123. An experiment to show the energy of the magnetic field. A current through the magnet builds up slowly, whereas one through the rheostat attains its full value almost instantaneously.

is worth while describing an experiment which illustrates it.

The experiment is conveniently made with a large electromagnet, the poles of which are bridged by a piece of soft iron (Fig. 123). The object of the bridge is to ensure, by giving the magnetic lines of force a complete iron circuit, that a given current in the coils of the magnet causes the largest possible magnetic field. By means of the switch S_1, shown in the figure, the current from the mains can be diverted either through the magnet or through the rheostat. The

rheostat is adjusted so that the steady current, measured by the ammeter, is the same through magnet or rheostat.

When, however, we switch on the current from the mains by closing S_2, we notice a striking difference in the way it *starts* to flow. If the current passes through the rheostat, the needle of the ammeter jumps rapidly to its final value. Its slight delay in response is only due to the inertia of the needle and moving coil, and is a fraction of a second in a good instrument. When the electromagnet is connected, although the needle finally reaches the same point it takes some seconds to creep to it. The current builds up slowly. The increasing magnetic field creates a back E.M.F. which opposes the applied voltage and prevents the current from immediately attaining its final value. Now, while the applied voltage is fighting this back E.M.F. it is *doing work*. It is like an engine setting a heavy train in motion, pulling against the inertia of the train. The work done is clearly required to create the magnetic field, just as the work done by the engine in getting a train going is represented by the kinetic energy of the moving train. On the other hand the current in the rheostat creates a very feeble magnetic field, and so it rises almost instantaneously to the value fixed by its resistance.

The energy of the magnetic field is also manifested when the current is cut off. In Fig. 124 a lamp is shown connected across the leads. The effect is more obvious if the lamp is one suitable for a higher voltage than that of the current supply, so that it only lights dimly. When the rheostat is put in parallel with the lamp by S_1, the lamp goes out directly the current is switched off at S_2. When the electromagnet is in

parallel, the lamp gives a brilliant flash as the current is cut off. The energy which gives the flash comes from the magnetic field. An induced E.M.F. tends to maintain the current which runs in the magnet, and when we switch off at S_2 the only path it can find is through the lamp. We see again that the energy of the magnetic field is like that of a moving mass. We have to work hard to build up the current, but once it is going it tends to run on, and will do further work before it ceases.

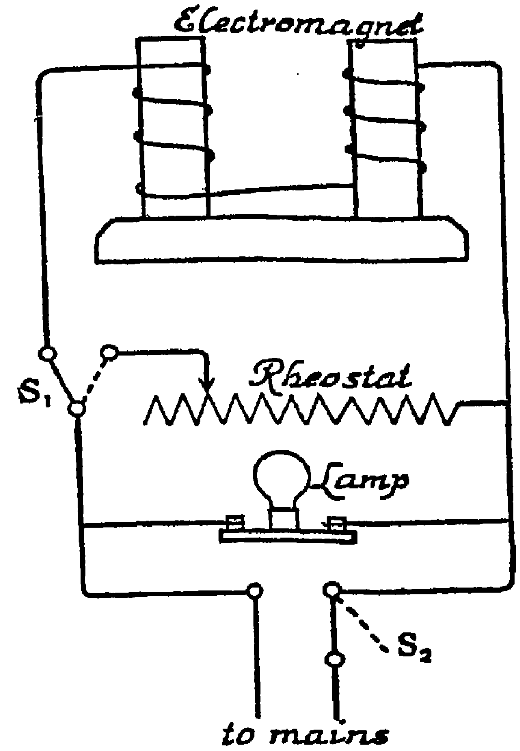


Fig. 124. Another experiment to show the energy of the magnetic field. When the main supply is cut off by S_2, the lamp gives a flash of light. The necessary energy comes from the magnetic field.

What determines the frequency of the oscillations? It depends upon the capacity of the condenser and upon the inductance of the circuit, the latter being a measure of the magnetic field energy due to a given current. A condenser of small capacity is like a stiff spring. The electromotive force builds up rapidly as it is charged, resisting the addition of extra charge. A circuit with a small number of turns is like a light mass, since, when increasing the current to a given value, little work has to be done in creating the feeble magnetic field, just as little work is required to set a light body in motion with a given velocity. Hence the oscillations are rapid when capacity and inductance are small, and slow when they are large. We can, in fact, get an enormous range in electrical oscillations, from frequencies so small that

they correspond to audible sounds (several hundred a second) to frequencies of one hundred million cycles per second or more.

3. THE TESLA COIL

The Tesla coil is a good example of an oscillating circuit which is very like the simple example shown in Fig. 122. The circuit consists of a condenser C and a few turns of wire I as shown in Fig. 125. A spark gap is placed in the circuit, and the leads from an induction coil[1] are connected to either side of the condenser. The induction coil produces a rising voltage, which charges up the condenser and finally reaches so high a value that a spark passes across the gap. The spark effectively short-circuits the gap for a brief time, owing to the number of charged molecules or 'ions' it produces along the track which it has followed. We therefore have a state of affairs very like that in Fig. 122*a*, the plates of the charged condenser being connected through an inductance. Oscillations are set up which die away, since they are not maintained. Each time the condenser is charged and a spark passes a fresh train of oscillations is set up, like striking the same note at regular intervals on a piano.

The oscillations produced by this arrangement are extremely rapid. The fact that the secondary of the induction coil is also connected to the condenser makes no difference to their frequency and may be left out of

[1] An induction coil resembles a transformer, having a primary of a few turns of thick wire and a secondary of many turns of thin wire around an iron core. The current in the primary is interrupted at frequent intervals by a special type of 'break.' Each time the primary current is abruptly stopped, a high voltage is induced between the ends of the secondary winding.

consideration. An oscillating current of high frequency cannot pass through a circuit with a large inductance like the secondary, because the back E.M.F. completely 'chokes' it. This is one of the effects which are characteristic of high frequency currents, and which makes their behaviour so unlike that of low frequency or direct currents. We must remember that a coil consisting of a number of turns is an effective barrier to the current, simply because the magnetic field cannot be created and destroyed so many times a second. As an analogy, you may think of a heavy door which moves very easily on its hinges. A light touch of one finger is able to open and close it slowly,

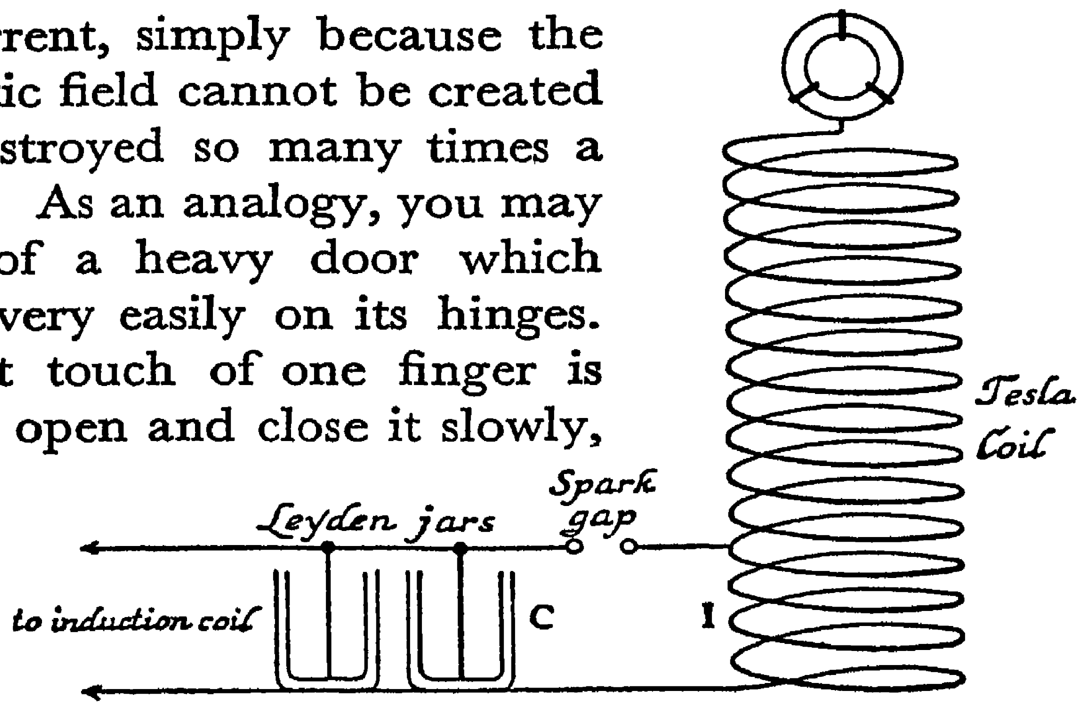


Fig. 125. The Tesla Coil.

but if you try to shake it backwards and forwards very quickly it will only move a fraction of an inch, even if you exert all your force with both hands.

In the Tesla coil (see Fig. 126, Plate 31) a large number of turns of wire, well separated from each other, are built on an insulating frame. In the apparatus shown in the figure the bottom four turns are being used as an inductance and are connected to the condenser and spark-gap. The upper turns then act as the secondary of a step-up transformer, of which the lower turns represent the primary. The voltage applied

to the primary is already high, and, owing to the secondary having so many more turns, the voltage at its upper end becomes very large indeed. When working the Tesla in a dark room, one can see 'brush' discharges fluttering from all points at the top of the coil where the potential fluctuations are greatest, the resistance of the air being broken down by the high voltage.

The Tesla coil is easily set up and illustrates many of the properties of high frequency current. One interesting feature is that we do not get an electric shock, even when we are taking quite a large current from it through our bodies. If one holds one end of a metal rod in the hand and brings the other near the top of the coil, a torrent of sparks can be taken from the coil accompanied only by a slight pricking sensation. The current does not produce a permanent effect in our bodies, because before the ions have had time to migrate any distance the current reverses and they move back again. We can show that the current is quite large by holding one lead from an electric lamp in the hand and presenting the other lead to the coil. Sufficient current to light up the lamp can pass through our body. Of course a current of this magnitude at low frequency would be fatal. We must take the precaution of grasping the rod or lead firmly. Large currents are passing, and if there is a poor contact between our fingers and the rod a little arc will form and burn the hand. Fig. 126 (Plate 31) shows a lamp being lit by a current which is passing through the hand of the experimenter.

If a tube containing gas at a low pressure is held near the Tesla coil while in action, the gas glows brilliantly.

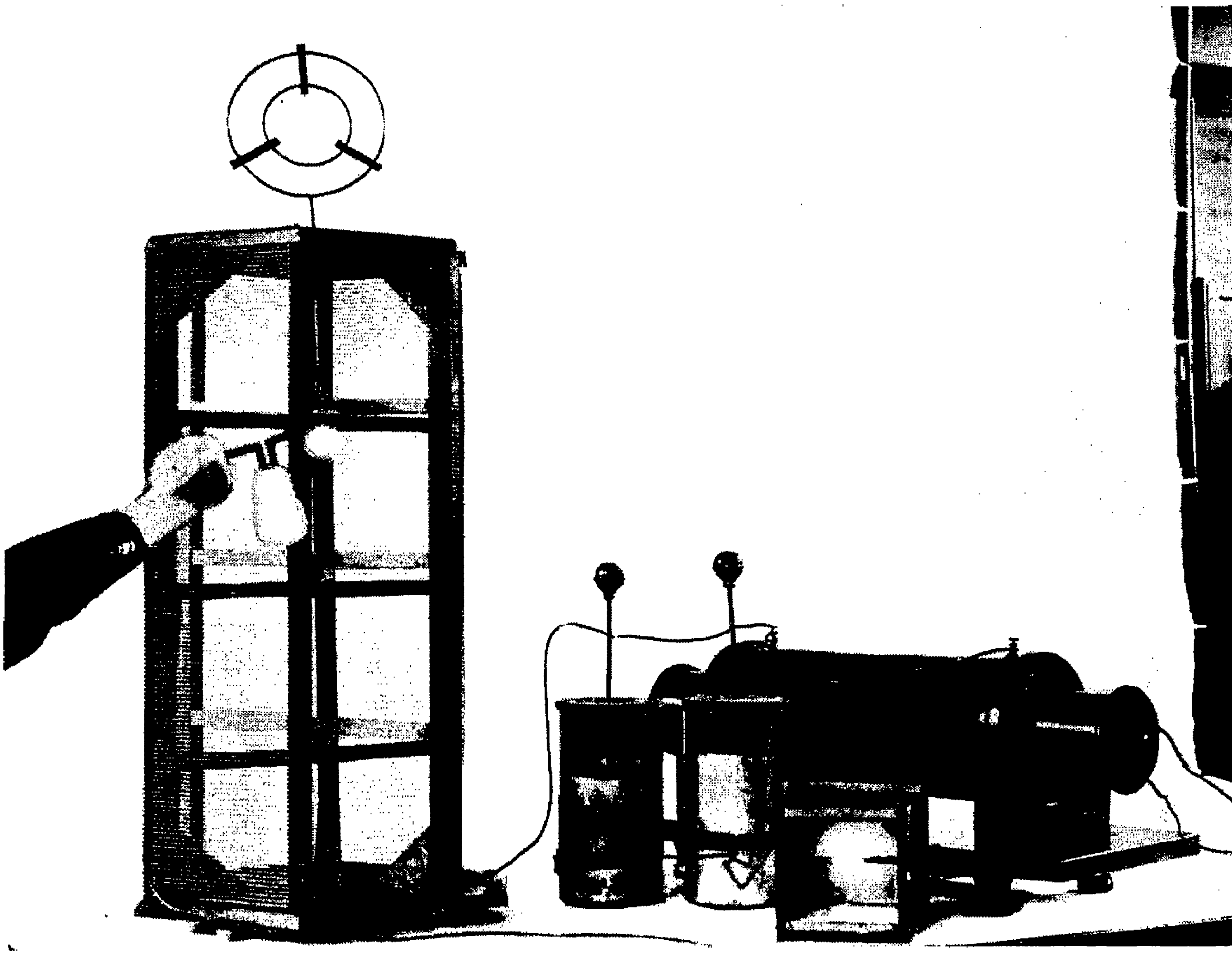


Fig. 126. The Tesla coil. A lamp is being lit by a high-frequency current drawn from the coil and passing through the arm. The induction coil, Leyden jars, and spark-gap can be seen

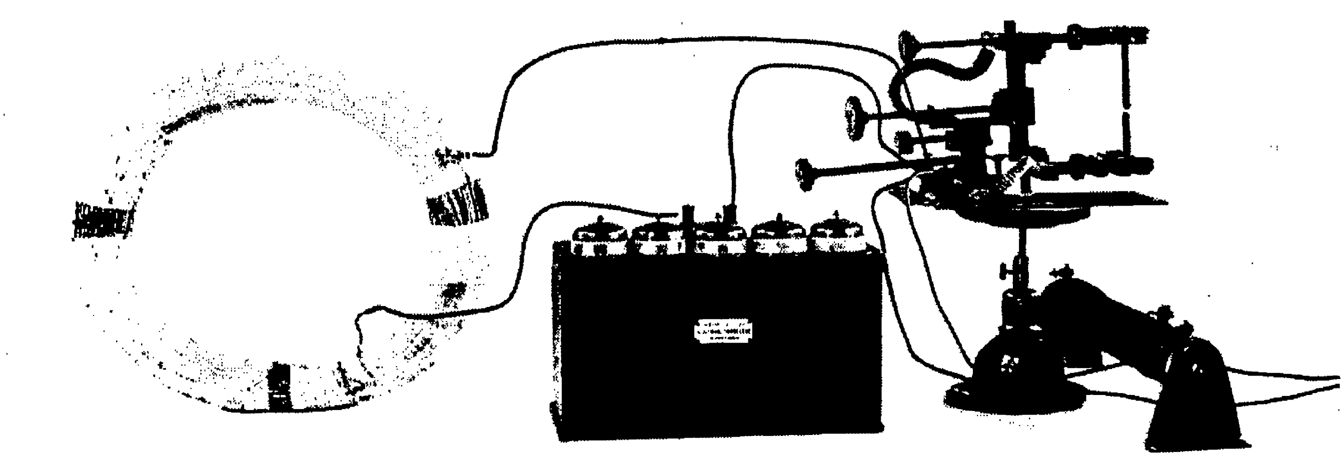


Fig. 128. The singing arc. The box contains condensers, which can be thrown in or out of the circuit by means of the switches

[*p.* 254

A discharge takes place in it, representing a current which is oscillating backwards and forwards in the tube and charging either end + and − alternately. The current is carried by positive and negative ions in the gas, which are produced by collisions in the way already described in the case of the spark discharge. The current is induced by the rapid alternations of magnetic field in the neighbourhood of the Tesla coil.

It may seem puzzling at first to understand how an appreciable current can run backwards and forwards in a tube like this, when there is 'nowhere for it to go to' at either end of the tube. Again, it is the high frequency of the current which makes it possible. The actual charge which accumulates at each end is very small, because the capacity is low, but if we remember that this charge changes ends in the tube a million times a second, we will see that its movements give rise to a considerable current. We may take as an analogy the number of seats sold per day in a cinema which is giving a continuous performance. It will depend partly on the seating capacity of the theatre and partly on the length of programme which people sit through. If the theatre could change its audience a million times a second there would be very brisk business at the ticket office, even though the seating capacity were small.

For the same reason, high frequency current will pass through a condenser, even if of small capacity, with practically no resistance. It charges and discharges one plate of the condenser, attracting opposite charges to the other plate, and so repelling equal charges of the same sign away from it, and this means that the current

passes straight on. This effect is very noticeable when a discharge tube is held near the Tesla coil as already described. The glow is particularly bright at the points where the tube is held by the fingers, which form one plate of a condenser with the gas on the other side of the glass wall as the other plate. The current passes freely across this condenser. The fact that a small 'choke' coil stops high frequency current but allows low frequency or direct current to pass, and that a small condenser stops low frequency and direct current but allows high frequency to pass, is useful when these types of current have to be separated.

We have seen that the Tesla coil is acting as a transformer as well as an oscillating system. A transformer designed for low frequency current is provided with an iron core which is magnetized in alternate directions by the current. An iron core is of no use in a high frequency transformer, because the magnetic changes in the iron cannot follow the fluctuations of magnetic field sufficiently quickly. We therefore simply need two coils of wire, arranged so that the lines of force produced by one pass through to the other.

4. THE SINGING ARC

The Tesla coil oscillates with a very high frequency because both capacity and inductance are so small. By increasing the capacity and inductance we can bring down the frequency until it comes within the range of frequencies in audible sound-waves. The 'Singing Arc' is an example of an oscillating circuit with a low frequency (Fig. 127), and it also illustrates one method of maintaining oscillation.

An arc is run from the mains with resistances in

series. As has been mentioned in an earlier chapter, we must always have a resistance in series with an arc since it has the characteristic property that the greater the current flowing between the poles the lower its resistance becomes. Hence there must be a steadying external resistance to prevent the current becoming too great. An oscillating circuit, whose capacity and inductance are very great, is connected across the arc. For instance, the condenser may be formed of many

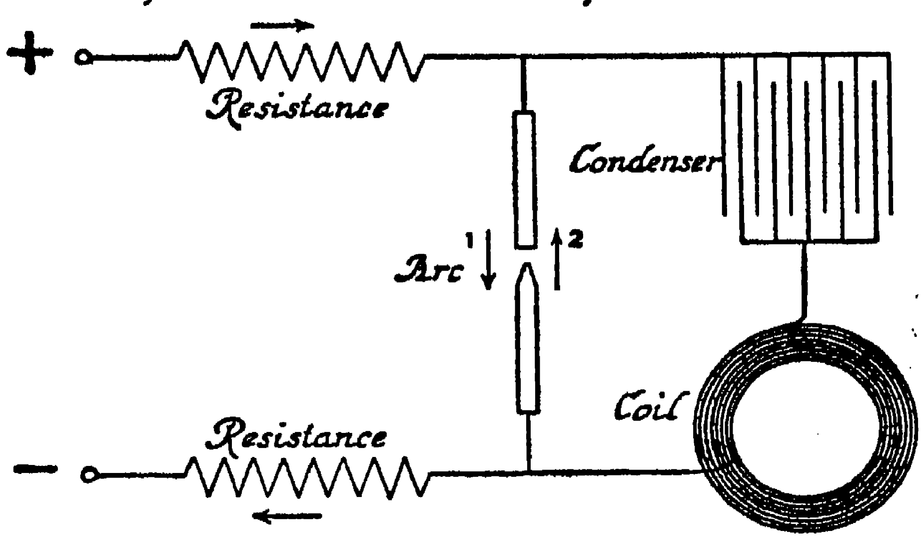


Fig. 127. The circuit of the 'Singing Arc.'

sheets of tinfoil separated by waxed paper, and the inductance may be a large coil such as is shown in Fig. 128 (Plate 31). When the arc is struck, the circuit is set in oscillation. The arc gives out a loud pure note due to the varying current, which is large when the current from the oscillatory circuit is in the same direction as that supplied to the arc by the mains, and is small when the two currents are in opposite directions, so that periodic fluctuations in temperature and pressure occur in the air round the arc.

The oscillations are maintained because the resistance of the arc becomes smaller when the current increases. Suppose the condenser is discharging by producing a

current in the direction of the arrow (1). The resistance of the arc decreases, as it is taking a larger current, and so the potential difference across it drops and the discharge of the condenser takes place more easily. When the current runs in the opposite direction (2), the resistance of the arc goes up, and this helps to divert the current from the mains to charge the condenser up again. The net effect is that the oscillating current gets a fillip in each cycle, like the series of pushes that keep a swing going or a pendulum beating. By having several condensers, and keys which throw them in or out of the circuit, one can play a tune on the singing arc.

An ordinary arc lamp cannot be used for high frequency oscillations because its resistance does not respond sufficiently rapidly to changes in current, but by arranging that the heat is rapidly conducted away from it, and by placing it in a magnetic field which is nearly strong enough to 'blow it out,' it can be made to work with a circuit in which the frequency is of the order of a million. Such arcs are called 'Poulsen' arcs.

5. MAGNITUDES OF QUANTITIES DETERMINING FREQUENCY

Now that we have studied examples of oscillating circuits, it is worth while getting some idea of the magnitudes of the inductances and capacities used to produce oscillations, and of the units in which they are measured. Though I have been careful to avoid mathematical equations in this book, I have given examples of the magnitudes of currents, potentials, and so on in terms of the units usually employed, because this is extremely useful practical knowledge and clears up one's ideas. One often finds that students who can

give brilliant answers on paper to questions which involve mathematical equations are quite vague about actual quantities, and do the wildest things in the practical laboratory in consequence. In the case of a subject like Physics it is more interesting to start by getting a good practical knowledge by handling apparatus, and then to study the mathematics, which is easier to follow when we can picture what it means and see how it makes exact calculations possible.

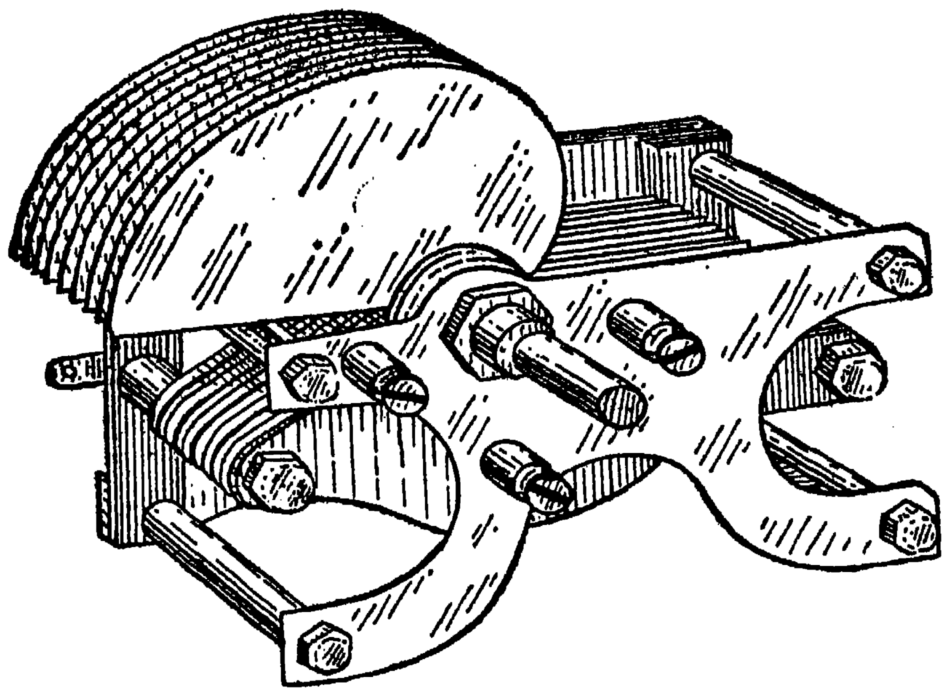


Fig. 129. A 'square law' condenser for tuning a wireless receiver.

The frequency of oscillations depends on capacity and inductance according to a law which is common to all forms of oscillation. Suppose we have a mass on a spring, for example, and want to make it vibrate *twice* as fast. We can do it either by shortening the spring to *one quarter* its length (which has the effect of making it four times as stiff) or by replacing the mass by one a *quarter* as heavy. The factor by which we must alter the spring or the mass is the 'inverse square' of the factor by which we wish to alter the frequency.

The same law holds for electrical oscillations. Shortening a spring so as to make it stiffer corresponds to reducing the capacity of the condenser, and reducing the mass corresponds to reducing the inductance of a circuit so that less magnetic energy is created by a given current. We must take a condenser of one quarter the capacity, or an inductance one quarter as great, in order to double the frequency. Alternatively we might halve both the capacity and the inductance, since this would bring in the same total factor of one quarter.

This law is illustrated very well by a certain type of condenser used in tuning wireless circuits (Fig. 129). The tuning is done by turning round one set of leaves so that they come between the other set, forming the opposite plates of an air condenser. If the plates were semi-circular, the capacity of the condenser would be proportional to the angle through which the movable plates have been turned. By making the plates of the familiar snail-like shape shown in the figure, it is arranged that the capacity increases as the square of the amount of turn. The period of the oscillations is therefore proportional to the amount by which the tuning knob is turned, and we can mark a uniform scale on it for tuning to various 'wave-lengths.'

The unit by which capacities are measured is called a 'microfarad.' A condenser with a capacity of a microfarad is a large affair. In electrostatic experiments condensers are usually formed by two plates separated by an air gap or a sheet of dielectric such as glass. As an example of magnitude, two plates a foot square separated by an inch form an air condenser with a capacity of about thirty millionths of a microfarad.

The capacity of the whole world, regarded as a vast condenser which can be given a charge,[1] is only 700 microfarads. On the other hand, if we build up condensers from many thin sheets of metal interleaved by sheets of paraffined paper, the capacity is so enormously increased that it becomes of the order of a microfarad. A condenser of this kind with a capacity equal to that of the world would go in a suitcase.

Inductance is measured in 'henries.' A dozen turns of wire of about a foot radius gives an inductance of one ten-thousandth of a henry. By having a large number of turns of wire lapped around an iron core, the inductance becomes of the order of a henry.

An oscillating circuit with 1 microfarad capacity and 1 henry inductance has a frequency of 159. By using the rules described above, the frequency for other capacities and inductances can readily be calculated.[2] For instance the singing arc circuit shown in Fig. 127 has a coil of $\frac{1}{50}$ henry inductance and a variable capacity with a maximum of 10 microfarads. When using the full capacity the note has a frequency of 357. The Tesla coil circuit, on the other hand, has an inductance of about one hundred thousandth of a henry and the Leyden jars have a capacity of about one thousandth microfarad, so that the frequency is about one and a half million. These figures will serve to give an idea of the quantities with which we are dealing. The frequencies used in wireless transmission lie between 200,000 and 1,000,000, or, as more usually expressed, between 200 and 1,000 kilocycles

[1] The world in this case is one 'plate' of the condenser and the rest of the universe is the other.

[2] The formula is: Frequency $= 159/\sqrt{LC}$, when L is measured in henries and C in microfarads.

per second. Quite small capacities and inductances therefore suffice to tune a wireless receiver.

The difference may now be clear between the alternating currents described in Chapter IV and the oscillating currents we are considering. If we start the current running in one direction in an oscillating circuit, a potential difference mounts up which presently drives it back again. The circuit itself makes the current rush backwards and forwards, and to keep it going we only have to supply a small impetus in each cycle. The frequency is determined by the circuit. On the other hand an alternating current dynamo is driving the current round a circuit first in one direction and then in the other, and the frequency is governed by the dynamo and not by the circuit. We can no more say that the alternating current from a dynamo is 'oscillating' than we can say that the Flying Scotsman oscillates between London and Edinburgh or the *Queen Mary* between Southampton and New York. People sometimes talk loosely of 'oscillating' in such cases but it is wrong to do so. If the Flying Scotsman were really oscillating, then by giving it a start at London it would bounce so hard off the buffer-stops at Edinburgh that it would get nearly all the way back to London again.

6. OSCILLATIONS KEPT UP BY VALVES

The thermionic valve has been described in Chapter II. We saw that it acted like a tap or sluice gate, by which a powerful electric current between the filament and plate can be regulated by a feeble one which alters the potential of the grid. The valve is extremely rapid in its response, and is therefore ideal for supplying

the impulses required to keep up a high frequency oscillation. The way in which it acts is shown in Fig. 130.

Suppose in the first place that we have a simple circuit like that in Fig. 130*a*. The inductance I and capacity C make up an oscillating circuit. A high tension battery B can be connected to the lower plate of the condenser by a switch S, giving it a negative potential. If we close the switch

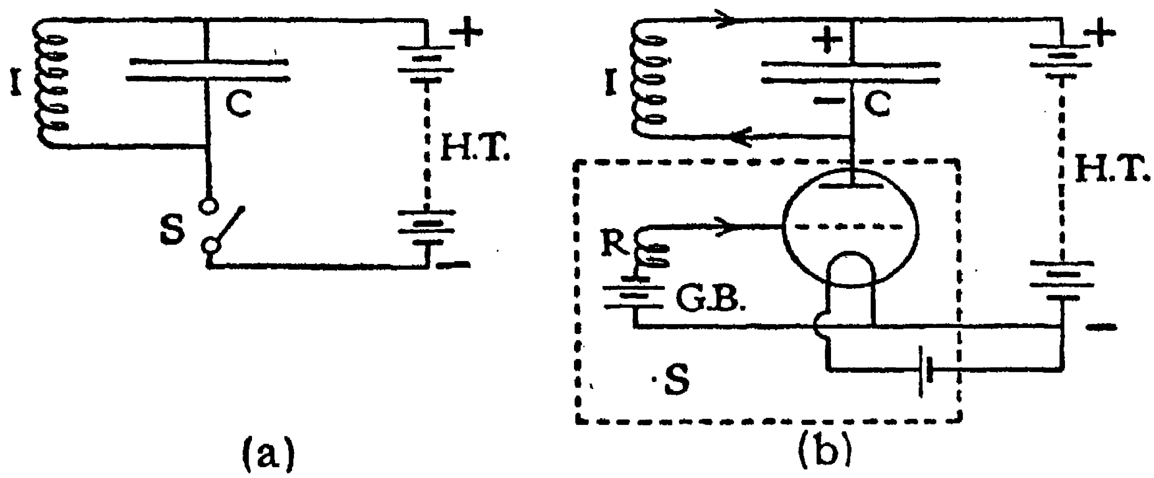


Fig. 130. Maintenance of oscillation by a valve.

for an instant C will be charged up, and will subsequently discharge through the inductance, charge up the other way, and discharge again in an oscillating manner. If left to themselves the oscillations die away. However, let us suppose we close the switch for an instant each time the lower plate of C is approaching its greatest negative potential. The battery will then charge it negatively a bit more, so keeping the oscillations up to full amplitude. It is as if every time a swing approached its highest point one were to give it a slight pull so as to make it rise a bit higher to a predetermined point, and so keep it going with a definite amplitude.

In order to adapt this arrangement to high frequency

oscillations, the switch S must open and close rapidly and must be worked by the oscillations themselves so that the impulses may come at the right moments. This is just what the valve does (Fig. 130*b*). The grid is connected to a coil of wire which is placed near the coil of the oscillating circuit so that magnetic lines of force due to a current in one coil pass through the other. The coils are said to be 'inductively coupled.' Picture now what happens when the oscillatory current has made the top condenser plate positive and the bottom plate negative, and is just about to stop and run in the reverse direction. Since the decreasing current in the coil I is failing to keep up the magnetic field, there will be an induced E.M.F. in the coil R trying to drive a current so as to preserve the field. If the coils are arranged as in the figure, you will see, by following the arrows, that this induced E.M.F. makes the grid positive. This encourages electrons to leave the filament, and most of these electrons escape through the grid, so making it possible for the battery to send an additional negative charge to the plate of the valve and charge up the condenser a bit more. I have enclosed by a broken line the part of the circuit in Fig. 130*b* which corresponds to the switch in Fig. 130*a*, to show that the valve is acting like the switch. The valve gives the charge on the condenser an extra boost during each oscillation and so keeps the oscillations going.

The battery marked GB gives the grid a negative 'bias.' For the greater part of each period it has so high a negative potential that it effectively keeps back the electrons. The grid only allows the electrons through when the induced positive E.M.F. overcomes

the negative potential of the bias; this happens just at the right moment to give the extra push at the end of the swing, when the oscillatory current is reversing in I, and C is charged. You are probably familiar with the little grid bias battery which is fulfilling this function in a wireless set.

Fig. 131 (Plate 32) shows a large valve and oscillating circuit which were kindly supplied by Messrs.

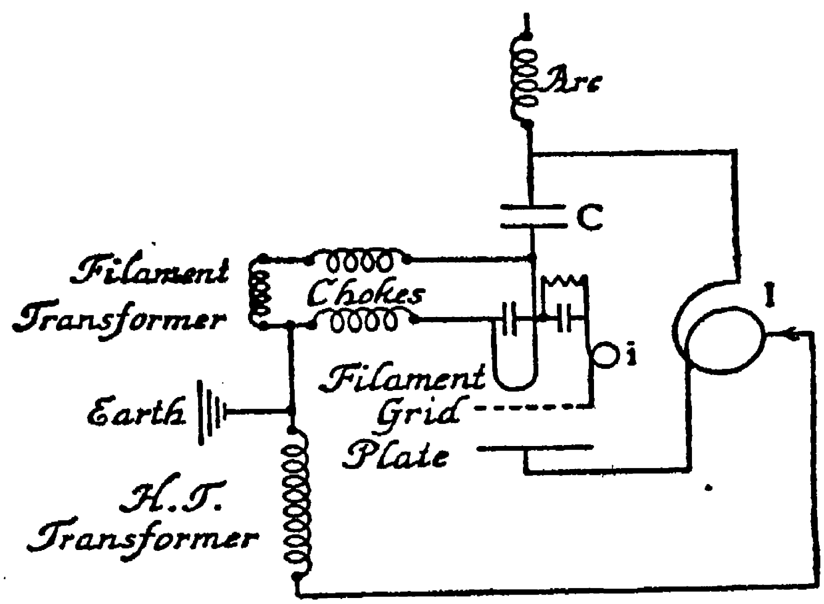


Fig. 132. The circuit of the apparatus shown in Fig. 131 (Plate 32). (*Metropolitan-Vickers.*)

Metropolitan-Vickers for the last Christmas lecture of the series. It takes about 30 horse-power to work this apparatus.

Fig. 132 gives a diagram of the circuit, which is somewhat different to that which we have considered above, but has sufficient points of resemblance to indicate how it works. The inductance of the oscillating circuit is due to a single loop I of thick wire which you can see on the right, and the condenser (*c*) consists of plates in the top of the tall cylindrical chamber. The filament, grid, and plate are in the lower portion of the same chamber, the plate being

lowest. The current in the filament is supplied by a transformer, with choke coils in series to stop high frequency currents from taking that path. A small coil (*i*) which is inductively coupled to the coil of the oscillating circuit, is connected to the grid, so as to vary its potential and maintain the oscillations as already explained. Instead of using a high tension battery for the plate, which would have to be a tremendous affair to supply the necessary 30 kilowatts at 7,000 volts, a high tension transformer fed by the alternating current mains is used. This means that the oscillations are only maintained during the part of the alternating current cycle when the transformer makes the plate positive, but the circuit makes hundreds of thousands of oscillations in this time, and so the valve works all right though not at full efficiency. The frequency is about thirty million.

The lower part of the apparatus is a series of pumps for withdrawing the air from the valve and condenser chamber. Small valves such as are used for wireless reception are sealed off once for all when they have been pumped out. So much power is developed in this large valve that one cannot depend on its remaining evacuated, and any gases set free inside must be pumped out continuously. The motor is driving an oil pump on the right, and this is reinforced by two 'molecular' pumps working with oil vapour whose action it would take too long to describe here. The condenser has to be placed inside the evacuated vessel because a discharge would take place between its plates if it were in air owing to the high voltages attained. The body of the cylindrical vessel is built of alternate cylinders of porcelain where insulation is

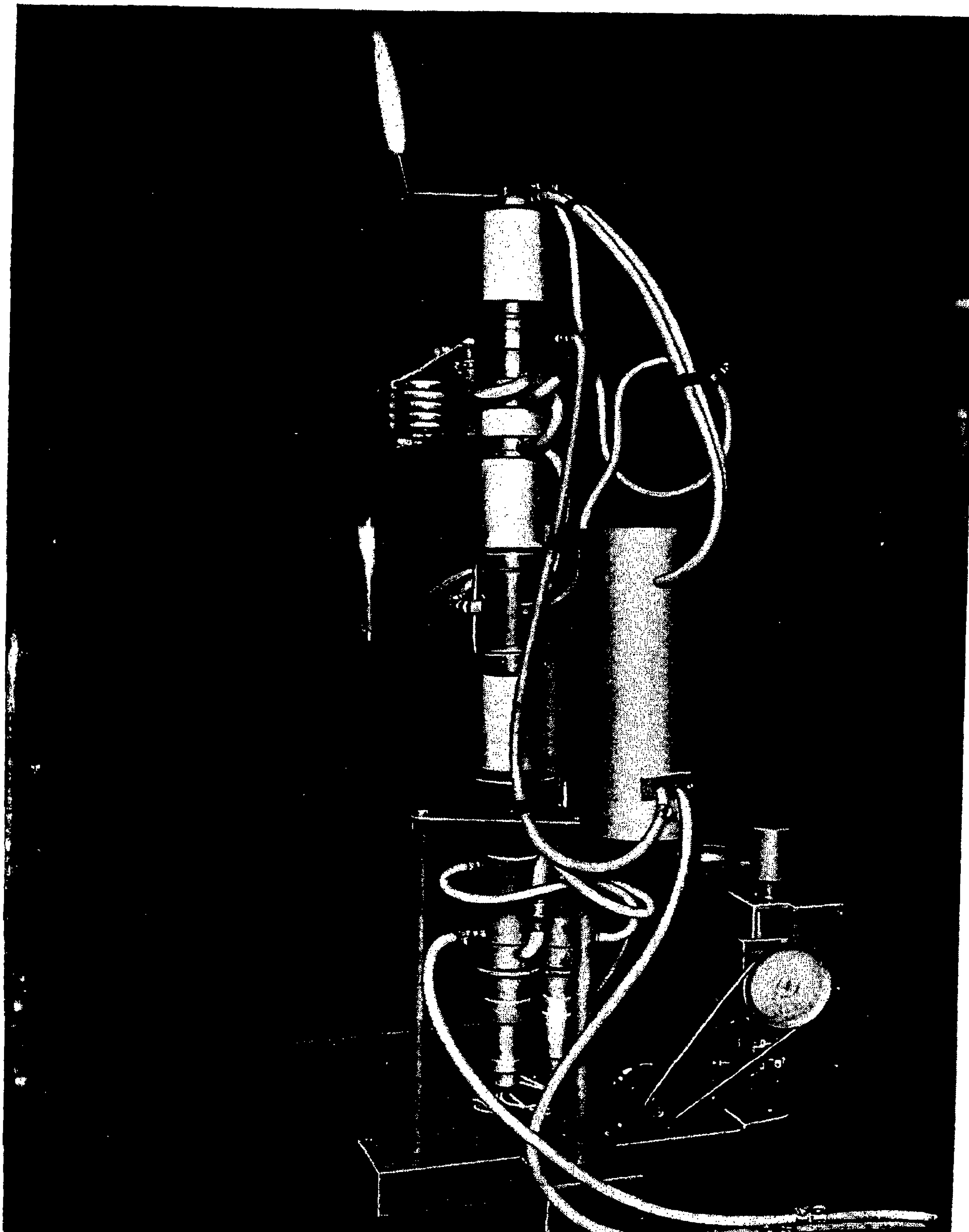


Fig. 131. A large valve maintaining oscillations of very high frequency (30 million). Induced currents are lighting the upper half only of the filament in the lamp held near the circuit (*Metropolitan-Vickers*)

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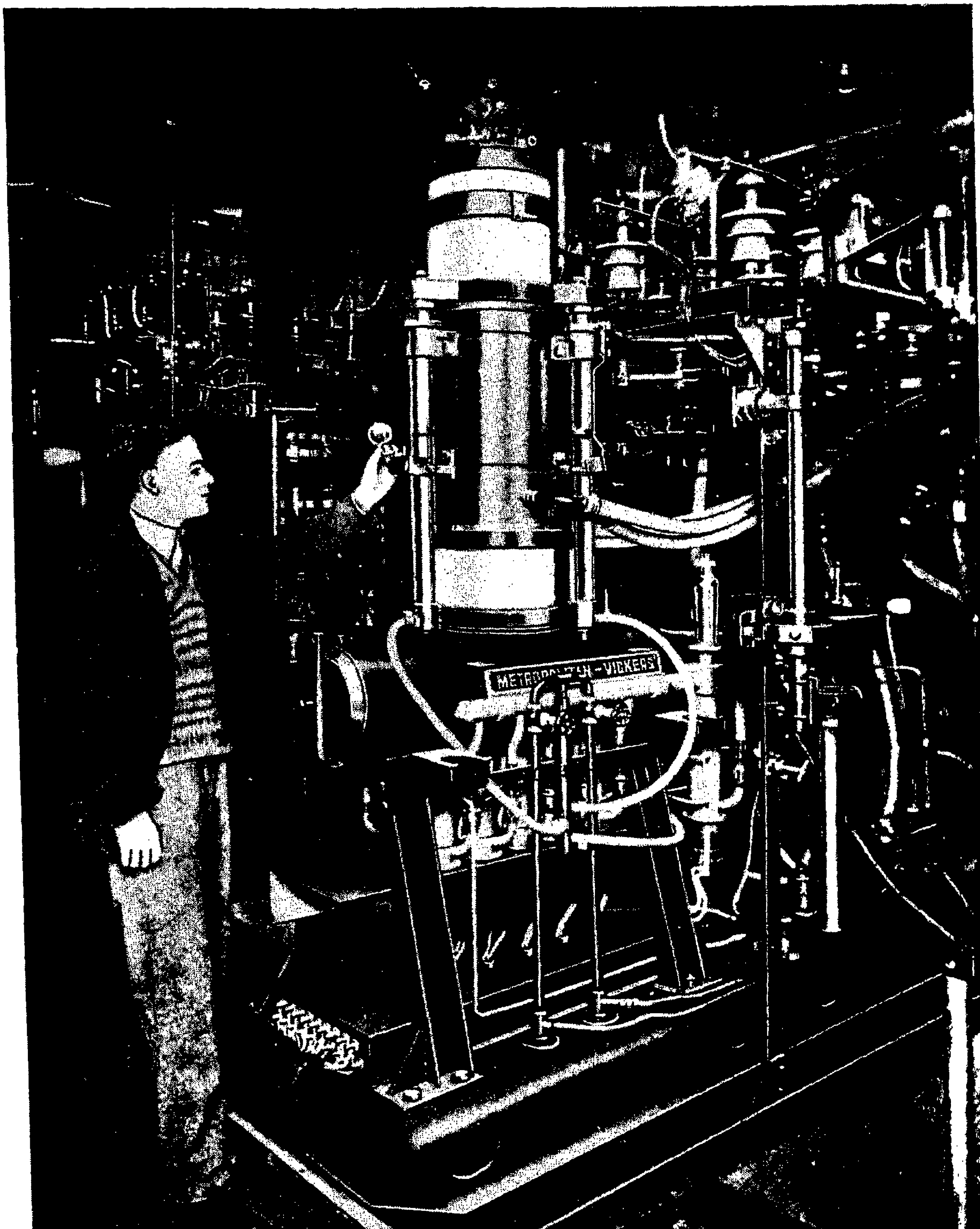

Fig. 134. A little valve and a big one. The little valve is one of the type familiar in wireless sets, and the big valve is for wireless transmission, maintaining oscillation in a circuit which radiates 500 kilowatts. A battery of pumps beneath the valve maintains the vacuum (*Metropolitan-Vickers*)

necessary, and of metal where connection has to be established to plate, grid, filament, and upper condenser plate (in order from the bottom upwards). The rubber tubes which you see writhing about in the illustration are carrying water to cool the various parts of the valve.

The upper plate of the condenser, right at the top of the apparatus, attains so high a potential that if a pointed conductor is attached to it a discharge passes into the air. This happens once in every cycle, or thirty million times a second, and causes a curious effect. A large flame, like that from a big bunsen burner, rises from the point. Electrons are rushing out of the point into the surrounding air and back again. When the high tension is supplied by a transformer, the flame gives out a loud hum corresponding to the frequency of the alternating current supply, but if the plate of the valve is raised to a steady high potential the flame is silent. By varying the plate potential by a microphone, in the way which is used in wireless transmission (see below), the flame can be made to talk and play music because the intensity of the discharge and the extent to which it heats the surrounding air goes up and down with the microphone currents.

On the left-hand side of the valve a man is holding by one end a straight-filament lamp such as is used for lighting shop windows, etc. One can just see his hand and sleeve in the photograph. The oscillating currents induce currents in the circuit formed by his hand and the filament which are sufficiently strong to light the lamp. The current is of course most powerful at the end where he holds the lamp, and fades away to

nothing at the bottom of the lamp, which is a blind alley, as you can see by the decreasing glow of the filament at the lower end. This experiment shows in a very striking way the curious effects produced by high frequency current. In a piece of wire about a foot long we witness a powerful current at one end and nothing at all at the other.

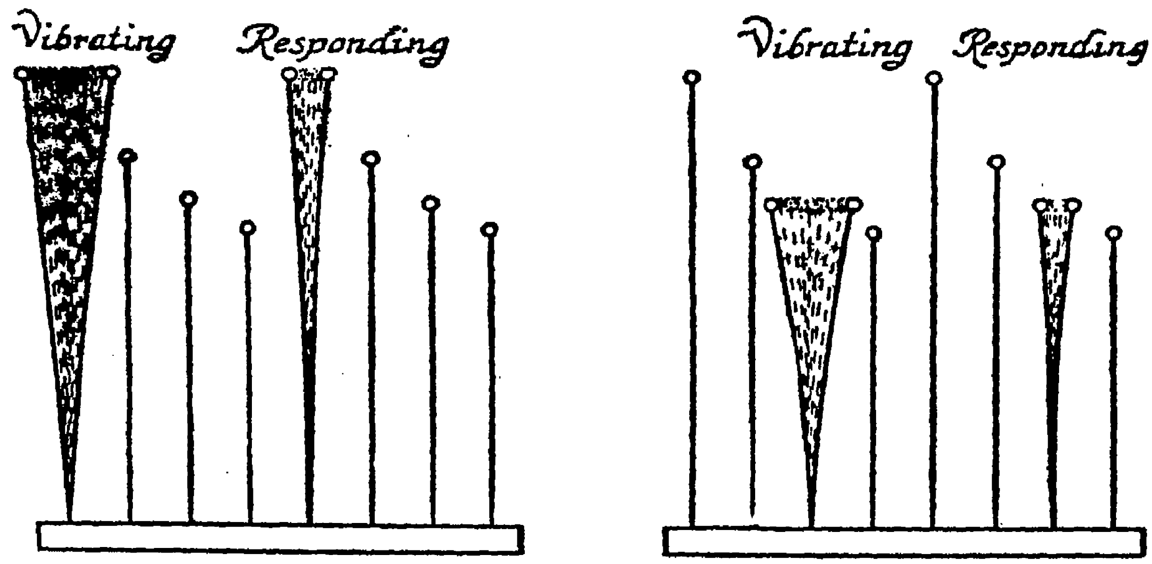

Fig. 133. An example of resonance. If any rod is set vibrating, the other rod of the same length responds.

7. RESONANCE

The magnetic fields due to an oscillating current induce currents in neighbouring conductors. If the conductor is one in which oscillating currents can be set up, and if by tuning it we make its natural frequency approximately the same as that of the first circuit, the effect is greatly increased by 'resonance.'

A simple model which exhibits resonance is shown in Fig. 133. A number of springy metal rods of identical material terminate in metal knobs of equal mass, all being fixed to the same baseboard. The rods are graded in size, there being a pair of each kind. The long rods vibrate slowly and the short ones fast. If we draw one of the rods to one side and let it go it

vibrates, and we will find that its twin picks up the vibration vigorously while all the other rods remain almost stationary. Whichever rod we set in vibration we will find that the other rod of corresponding length vibrates too. The vibratory rod is shaking the whole baseboard backwards and forwards slightly, giving impulses to the ends of the other rods. In general, these impulses do not set them in motion with an appreciable amplitude, but in the case of another rod of equal length the timing is just right. If the first impulse pushes it in a certain direction, the next one comes when it has made one swing, and is ready to get a push in the same direction again, so that its amplitude mounts up.

One can illustrate resonance very well with a piano. Open the lid, press down the loud pedal so that the strings are free to vibrate, and sing a pure vowel sound near the strings (ah, ee, oo). Not only will the piano give back the same note after the voice has ceased but it will also give back an approximation to the same vowel, incidentally showing that vowels are characterized by definite notes, as we saw in the last chapter. The strings which vibrate with the same frequency as notes in the complex sound of the voice are set in agitation, and when the voice ceases they continue the sound. They *resonate* to the notes in the voice.

The oscillations produced by the large valve just described can be used to demonstrate resonance in a striking way. An oscillating circuit is formed of a variable plate condenser, and a few turns of wire and a lamp is included in the circuit. If the circuit is in the neighbourhood of the valve, and is tuned in by

altering the capacity of the condenser, the lamp will light up. Considerable care must be taken in the case of a powerful high frequency oscillator to see that there are no conductors in the neighbourhood which may respond too vigorously in this way. A length of cable, or a water- or gas-pipe which is of the right dimensions, may become so hot as to cause a fire.

This violent response of one oscillating circuit to another, in which a large fraction of the energy used to maintain the oscillations of the first circuit is picked up by the other, only occurs when the circuits are close together, i.e. when their distance apart is not many times greater than the dimensions of the inductances. It still exists in an enfeebled form, however, when they are a long way apart, and this is the basis of 'Wireless.'

8. WIRELESS

We cannot go into the methods used in 'Wireless' in any detail because once one embarks on a description of them with examples of the circuits one is led into an account which would be as long as the whole of this book. On the other hand, if the reader has appreciated the principles which I have attempted to explain in this book, it will be found that wireless has lost its air of mystery. A book on wireless will then become an entrancing account of ingenious devices used to overcome technical difficulties. I will content myself here by tracing in a descriptive way the links between the reception of sound by the microphone in a broadcasting studio and the reproduction of the same sounds by the loud speaker of a receiving set.

The transmitting station has a powerful oscillating

system linked to the aerial. The oscillations are produced by a large valve such as that shown in Fig. 134 (Plate 33). The oscillating system is tuned to the frequency which has been allotted to that particular station, and which you will see opposite the name of the station in the list of wireless programmes given by our daily papers. As mentioned above, the frequencies are given in 'kilocycles' so as to avoid very large numbers. A kilocycle is one thousand cycles, so that, for instance, 'Droitwich National, 200 kcs.' means that the current is rushing up and down the aerial at Droitwich 200,000 times a second.

We must now see how the characteristic frequencies of speech and music are impressed upon the oscillations at the transmitting station, and how they are repeated by wireless receiving sets. The microphone in the broadcasting studio turns the variations of pressure due to the sound waves into variations of electrical current. These variations are amplified by a succession of valves, being fed at each stage to the valve grid, and the more powerful plate current variations are then used to affect the grid of the next valve. Finally they vary the plate potential of the large valve which is maintaining the oscillations in the aerial. The final result is that the *amplitude* of the oscillations (which depends on the plate potential) goes up and down in sympathy with the variations of air pressure received by the microphone. It must be remembered that the oscillations are much more rapid than the air vibrations so that the circuit makes perhaps a thousand oscillations while the diaphragm of the microphone moves once backwards and forwards. It is as if we were sending a message with a shrill whistle, not by varying

its pitch (which remains constant) but by blowing it harder or more gently, and so varying its loudness. The receiving set performs the same operations in the reverse order. It picks up the oscillations of varying amplitude, turns the variations of amplitude into variations of electric current, and finally by means of the loud speaker it makes the variations of current reproduce the sound-waves.

The methods which are chosen here as illustrations

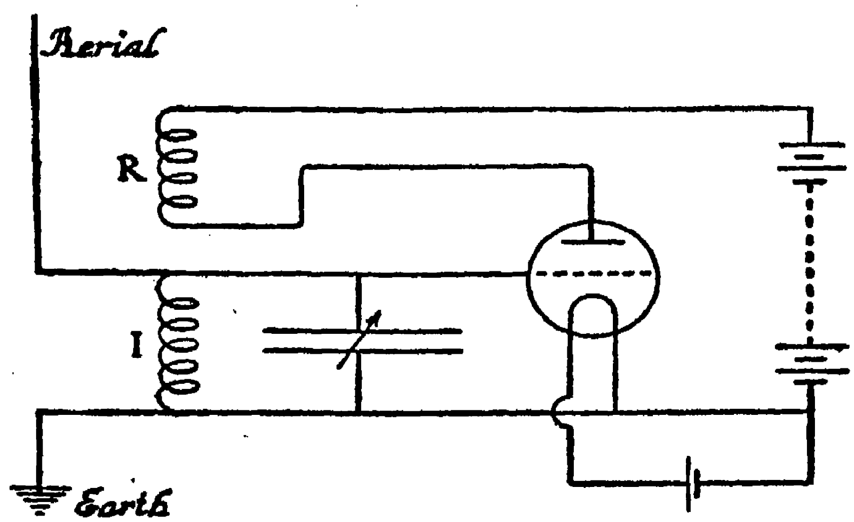

Fig. 135. The principle of tuning a wireless circuit so as to pick up oscillations sent out by the transmitting station.

of the three stages in reception of wireless signals have been superseded by far more efficient modifications in modern wireless sets, and are only given to illustrate principles. In the first place, the high frequency oscillations sent out by the transmitting station must be separated from those of other frequencies and picked up. The aerial and earth leads are connected as shown in Fig. 135 to a circuit whose natural frequency can be adjusted by the variable condenser. The circuit is tuned to the frequency of the transmitting station by adjusting the capacity of the condenser, when the oscillatory currents induced in it become much more powerful by resonance. The effect is further increased

by the valve. The circuit is itself capable of maintained oscillation. Oscillatory currents alter the potential of the grid, and so produce much more powerful variations of plate current, and these currents passing through the reaction coil R will maintain the oscillations if the coupling between R and I is sufficiently 'close,' i.e. if currents in R induce sufficiently strong E.M.F.'s in I. The coupling can be altered by adjusting the relative positions of R and I or by other methods. If it is too close, the set maintains its own oscillation and produces a roaring noise in the loud speaker. If now the coupling is reduced till self-oscillation just ceases, the receiver will be extremely sensitive to oscillations coming from outside. To put it in a graphic way, any oscillatory currents picked up by the aerial are very strongly encouraged to become large by the coupling between R and I. The net effect, then, of adjusting the capacity and the coupling is to produce strong oscillatory currents in the receiving set which rise and fall in amplitude in obedience to the varying strength of the oscillations sent out by the transmitting station.

The next step is to convert these variations in amplitude of the oscillating current into variations in strength of a current flowing in one direction by 'rectification.' One way of doing this is shown in Fig. 136.

The grid of a valve is connected to the receiving circuit through a condenser which allows oscillatory currents to pass, and the condenser plates are connected together by a high resistance called a 'grid leak.' Each time the grid is made positive by the oscillations in the receiving circuit, it attracts electrons to itself from the

filament and so picks up a negative charge. If there were no grid leak this negative charge would mount up and finally would stop any current through the valve, because the grid cannot get rid of its electrons inside the valve and cannot discharge through the condenser. The grid leak, however, allows the charge to escape slowly. The result of this arrangement is that, when the oscillations are strong, the grid attracts many electrons and acquires a high negative charge, and when they are weak its charge is small. The

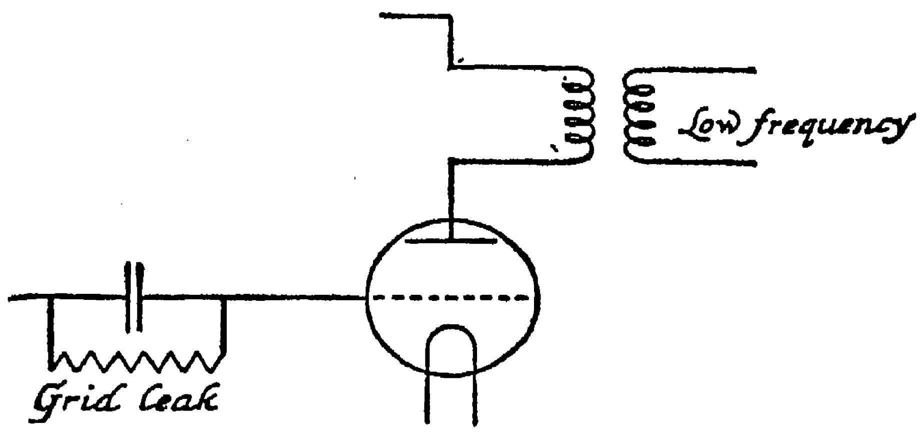

Fig. 136. A method of 'rectification.'

following analogy may help. Suppose we are pumping up a tyre which has a puncture representing the grid leak. We pump always at the same rate, but sometimes use long strokes (strong oscillations) and sometimes short strokes (weak oscillations). In the first case the tyre will be kept highly inflated, in the second case it will be soft. Now the average current through the valve depends upon the average potential of the grid, being smaller the more negative the grid. We have therefore turned the variations in amplitude of the oscillations into variations of current running through the valve. There are other ways of achieving the same purpose, such as by using a characteristic of the valve called the 'anode bend,' but the above will serve as an

illustration of how it can be done. The point to realize is that the transmitting station turns the variations in microphone current into variations in amplitude of high frequency oscillations, and that the receiving circuit picks these up and turns them back again into varying currents. The net effect is just the same as if we connected the broadcasting microphone to the loud speaker by a telephone cable.

In the final stage, the current variations are amplified

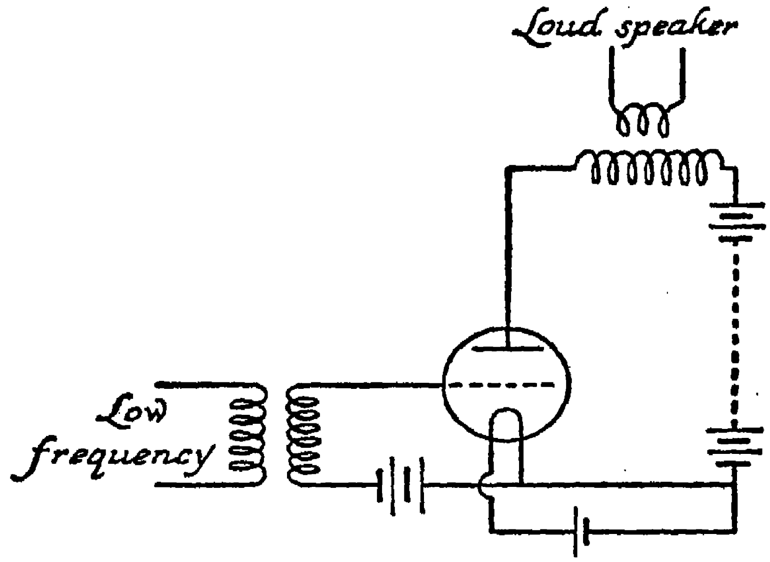

Fig. 137. A method of low frequency amplification.

by a 'power valve' (Fig. 137) and are then used to work the loud speaker, which thus reproduces the sounds received by the microphone in the transmitting studio.

It is a far cry from the simple devices described here to the complex circuits of a modern receiving set such as one can study in the technical journals. Wireless telephony depends, however, on refinements of these devices, the maintenance of oscillations by valves, the response of tuned circuits, and the amplification by valves of high frequency and low frequency currents. It is founded upon the marvellously adaptable control of current by a thermionic valve.

9. WAVES

Energy in some form is being sent out by a wireless transmitting station. Power is being used to drive it, and although some of this power is wasted in heating the circuits there is a large balance otherwise unaccounted for which we say is 'radiated' by the station. A minute fraction of this energy turns up again in receiving sets. In the experiment described at the end of §7, the circuit in which the lamp is placed is obviously picking up a great deal of energy which has somehow travelled to it from the valve. It is clear that we could get all the energy back again if only we had an effective means of picking it up.

Now the energy does not travel instantaneously from one place to another. Though the radiation travels very fast, it has a definite speed. For instance, it is possible to send out a signal from a transmitting station and to pick up the same signal on a near-by receiving station after it has gone once round the world; it takes about one-seventh of a second on this journey. The radiation travels with the velocity of light, and in fact is of the same nature as light. Alternatively we may say that atoms which are giving out light, as for instance the atoms of luminous gas, are tiny wireless transmitting stations broadcasting on their own characteristic and extremely high frequencies. The retina of the eye is covered with little receiving sets which turn the signals into electrical currents conveyed to the brain by the nerves.

If we move something up and down with a definite frequency on the still surface of a pond ripples spread out. After a time, fixed by the rate at which the

ripples travel, a cork floating at a distance on the surface of the water will begin to oscillate up and down with the same frequency as the cause of disturbance. We find just the same thing in the case of this electrical form of radiated energy. The transmitting station makes currents oscillate up and down its aerial, and some form of energy spreads out which makes currents dance up and down in a distant conductor after the lapse of a time, which shows that the influence is travelling at a definite rate. We cannot trace what is happening between the two places. There is no way of 'seeing' the energy while on its journey, because it only makes itself apparent when it is picked up by a receiving set, but it behaves so like wave motion that we say that the transmitting station is radiating *electromagnetic waves.*

The waves travel at 3×10^{10} centimetres a second, or 300 million metres a second. If the frequency of the transmitting station is one million cycles a second, each wave must be 300 metres long, because there are a million of them in a stretch of 300 million metres. This is the meaning of the 'wave-length,' which is an alternative way of describing the radiation from the station. We see, for instance, in a list of stations

North (449·1 Metres: 668 kcs.).
Droitwich National (1,500 Metres: 200 kcs.).
Regional (342·1 Metres: 887 kcs.), etc.

If we multiply the number of kilocycles by 1,000, and multiply again by the wave length, the result is in each case 300 million metres — the distance travelled by the waves in one second.

Fig. 138 may help towards understanding the nature

of these electromagnetic waves. Suppose we have a chain made of alternate links of copper and iron, and start oscillating currents running round the first copper ring. These currents magnetize the first iron ring first in one direction and then in the other. The fluctuating magnetization of the iron ring produces oscillatory currents in the second copper ring, which in turn magnetize the next iron ring and so on. A signal made by a group of reversals of current in the first ring will

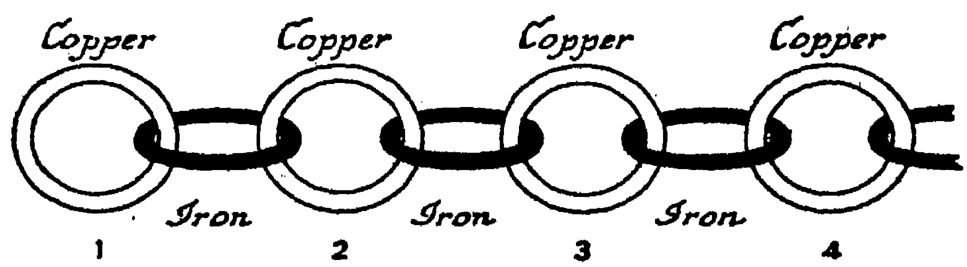

Fig. 138. Diagram to illustrate the nature of electromagnetic waves.

run along the chain just as waves run along a long stretched rope if one end is waggled. We must now try to picture the same thing happening when the copper and iron rings are not there. It is easy to do without the iron rings, because their only function is to increase the magnetic effects. One copper circuit will still induce currents in the next when the iron is absent. It is harder to eliminate the copper rings in our picture, and I can only hint at what is taking place. We have seen that a high frequency current passes freely through a condenser, although no electrons travel from one plate of the condenser to the other. What happens is that the electrostatic lines of force in the condenser first stretch in one direction, then disappear, then stretch in the reverse direction, disappear again, and so on. The *alternating current* in the wires leading to the condenser plates becomes a *fluctuating electric field* between the plates. Maxwell realized that such

fluctuations in the electric field are equivalent to a fluctuating current and have the same magnetic effect as a current. Hence the copper rings in Fig. 138 can be left out too, the currents we have supposed to run in them becoming fluctuating electric fields. In a wave motion, as in an oscillating system, energy appears in two forms. In a sound wave, for instance, it may be stored up in the compressed air or be the kinetic energy of the moving air. In the present case, the energy is either electrostatic or magnetic. The fluctuating electric fields produce magnetic fields, and the fluctuating magnetic fields in turn produce electric fields, and the disturbance travels as a wave.

Maxwell calculated the rate at which such a disturbance would travel in free space, and proved that the rate was the same as the speed of light. Wireless waves, radiant heat, light, X-rays, and the γ-rays from radioactive substances are all forms of electromagnetic radiation, only differing in their frequency which is least for the wireless waves and greatest for the γ-rays.

In wireless telegraphy and telephony waves are sent out by transmitting stations and are picked up all over the world, as if it were one vast whispering gallery. We have seen how valves are used for this purpose, but even with these marvellously delicate recorders of faint signals wireless would be impossible were it not for two factors.

In the first place, the whispering gallery is extremely quiet. If it were already full of electrical tremors due to natural causes, they would drown the wireless signals, and it would be of no avail to increase the sensitiveness of our recording apparatus. We should not be able to hear the signals owing to the general

background of clamour. As it is, we are launching the wireless waves upon a calm sea. The only breezes which ruffle its surface are due to thunderstorms, and their effects are so local that we only hear faint atmospherics unless they are very close.

In the second place, the whispering gallery has a ceiling, and this ceiling makes it possible to send waves from one side of the earth to the other. If it were not there, the waves from a transmitting station would only be picked up at near-by points, for distant stations would be shielded by the intervening earth round whose curvature the waves could not travel. However, there is a region of ionized air a hundred miles above our heads called the Heaviside Layer, which reflects the wireless waves in the same way that a polished metal surface reflects light. The waves are deflected downwards by the layer and travel round the curvature of the earth beneath it, so reverberating over the whole of the world's surface.

CONCLUSION

Wireless telephony represents one of the latest developments of the use of electricity. If we try to sum up the new power which we have got by making electricity serve our purposes, we may call it a power of *transmission*, of sending an influence to a distant place. The network of power cables spread across the country is the outward sign that all may share in a common pool of energy. This energy may be transmitted from coal which is burning or water which is falling hundreds of miles away. The telegraphs and cables make it possible to send messages almost instantaneously to any part of the world. Finally, the still more delicate control of

electric current by the valve has inaugurated a new era with a far-reaching effect on our lives. Not only messages, but also personality, can be broadcast to listeners all over the country. Statesmen, leaders of thought, famous exponents of the arts, who in the past were only names to the majority of people, are now known in a much more personal way because all can hear them. Presently listeners will probably be able to see them at the same time, for general television is on the way.

In all these cases electricity is the connecting link between one place and another. The potentialities of this new factor in our lives should be widely appreciated, and I have written this book in the hope that my readers may find it helps them to grasp the natural laws, the patient study of which has led to such remarkable developments.

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Explanations of technical terms are shown in heavy type